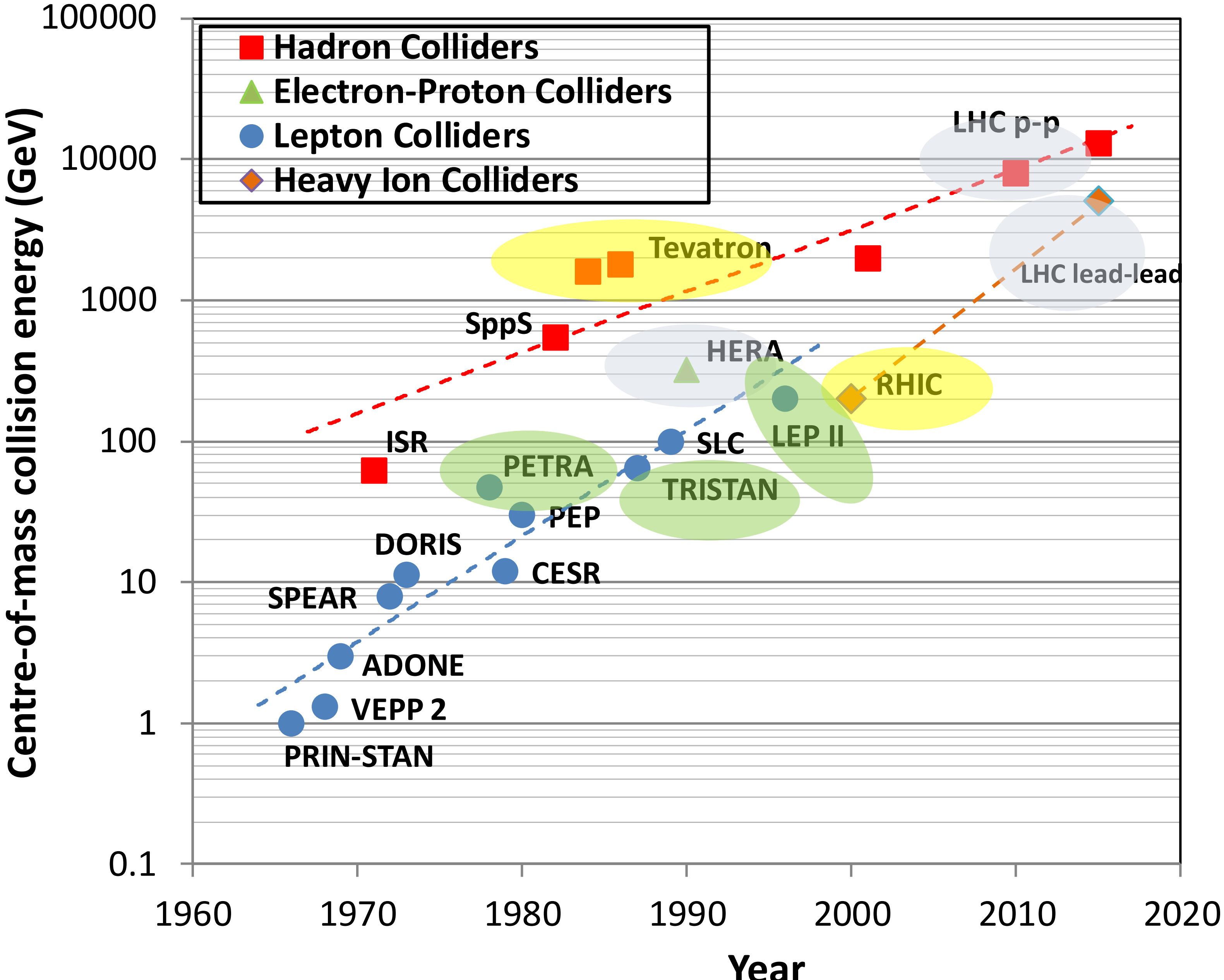
Innovative Accelerator Technologies

Frank Zimmermann, CERN

2022 LHC Days in Split, 7 October 2022

Colliders constructed & operated



A. Ballarino

Colliders with superconducting RF system

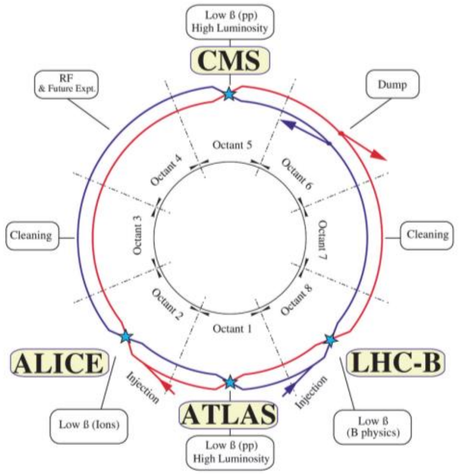
Colliders with superconducting arc magnet system

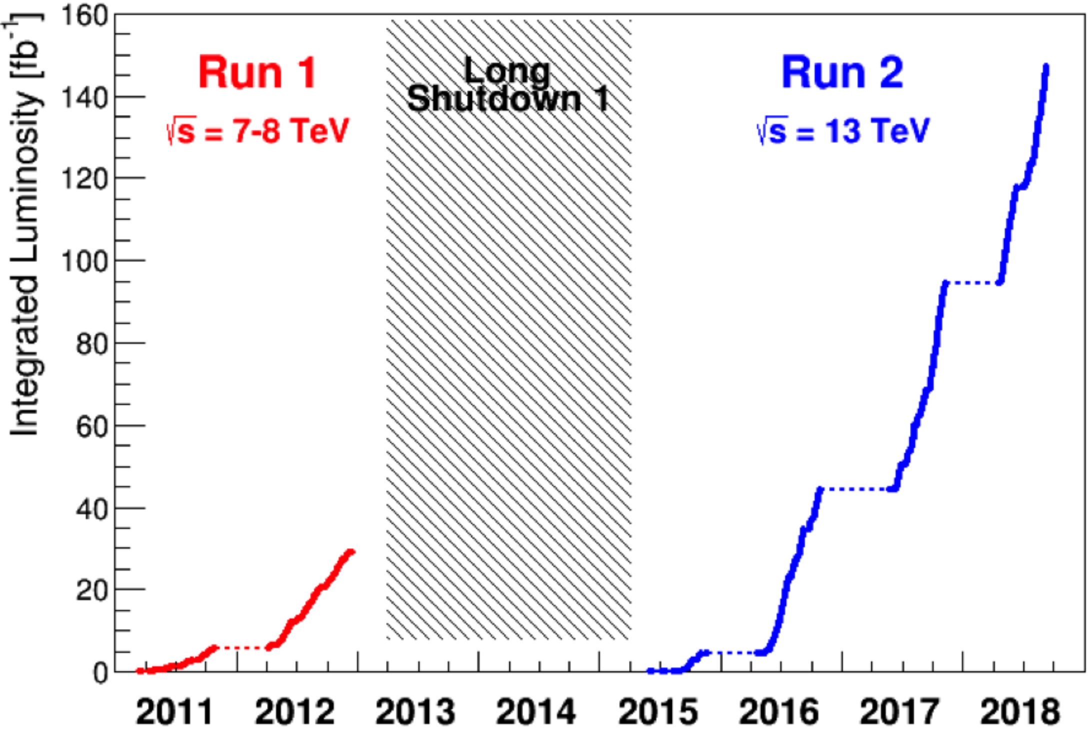
Colliders with superconducting magnet & RF

advances by new technologies and new materials

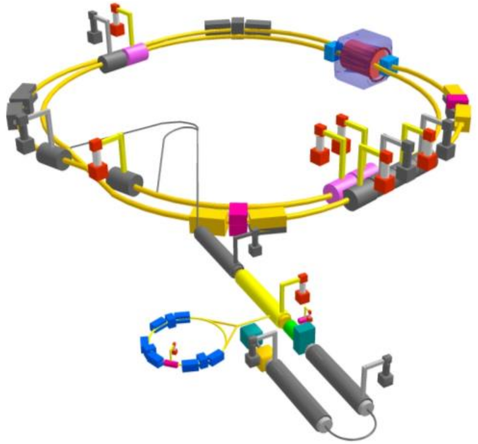
Collider State of the Art

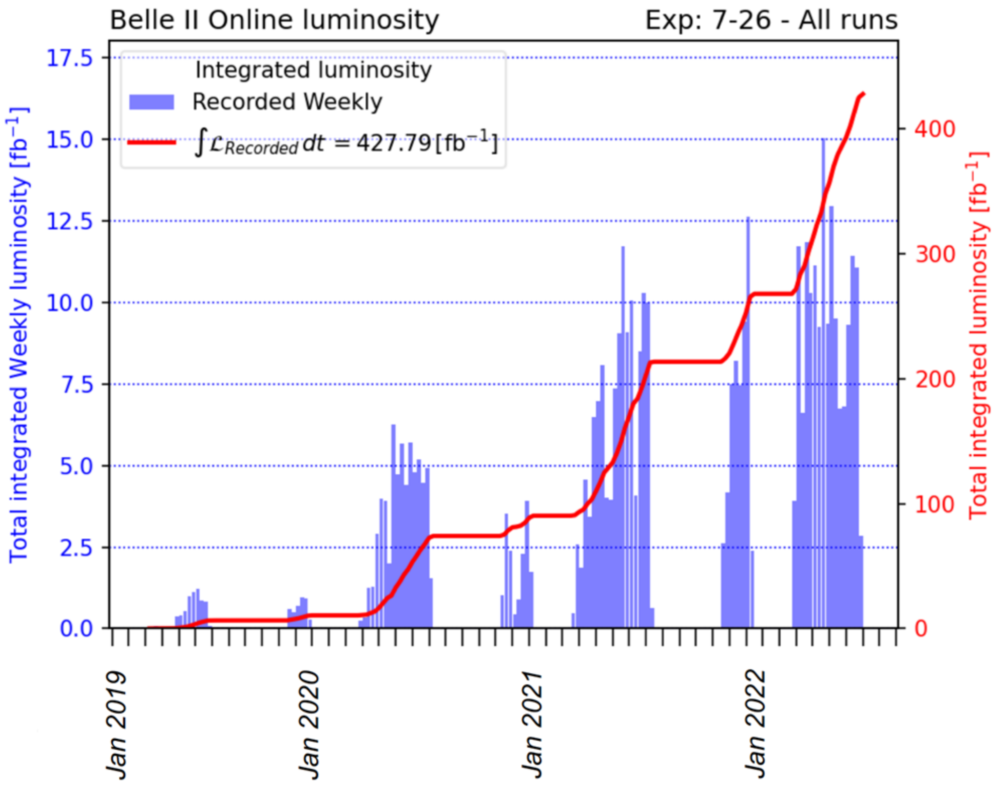
Large Hadron Collider
LHC





SuperKEKB

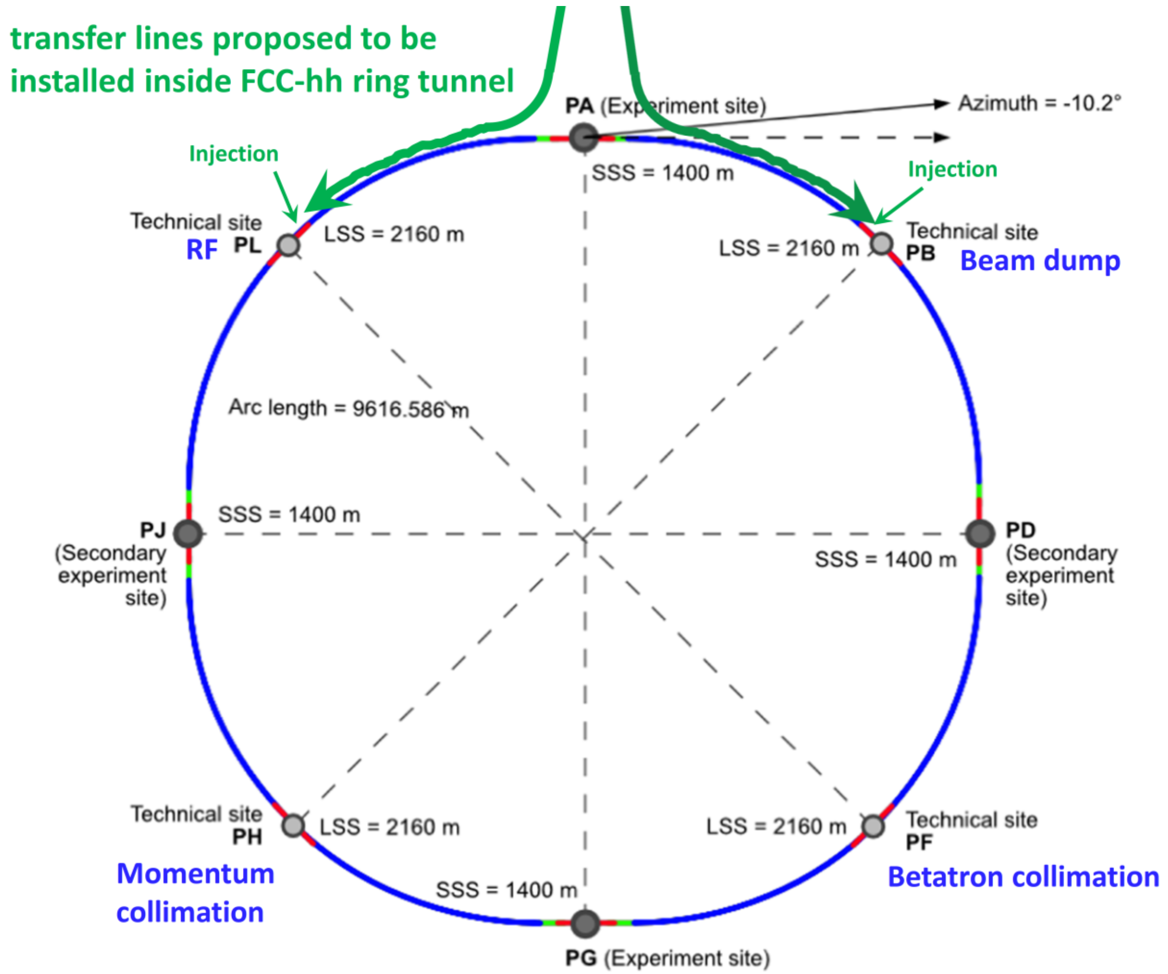




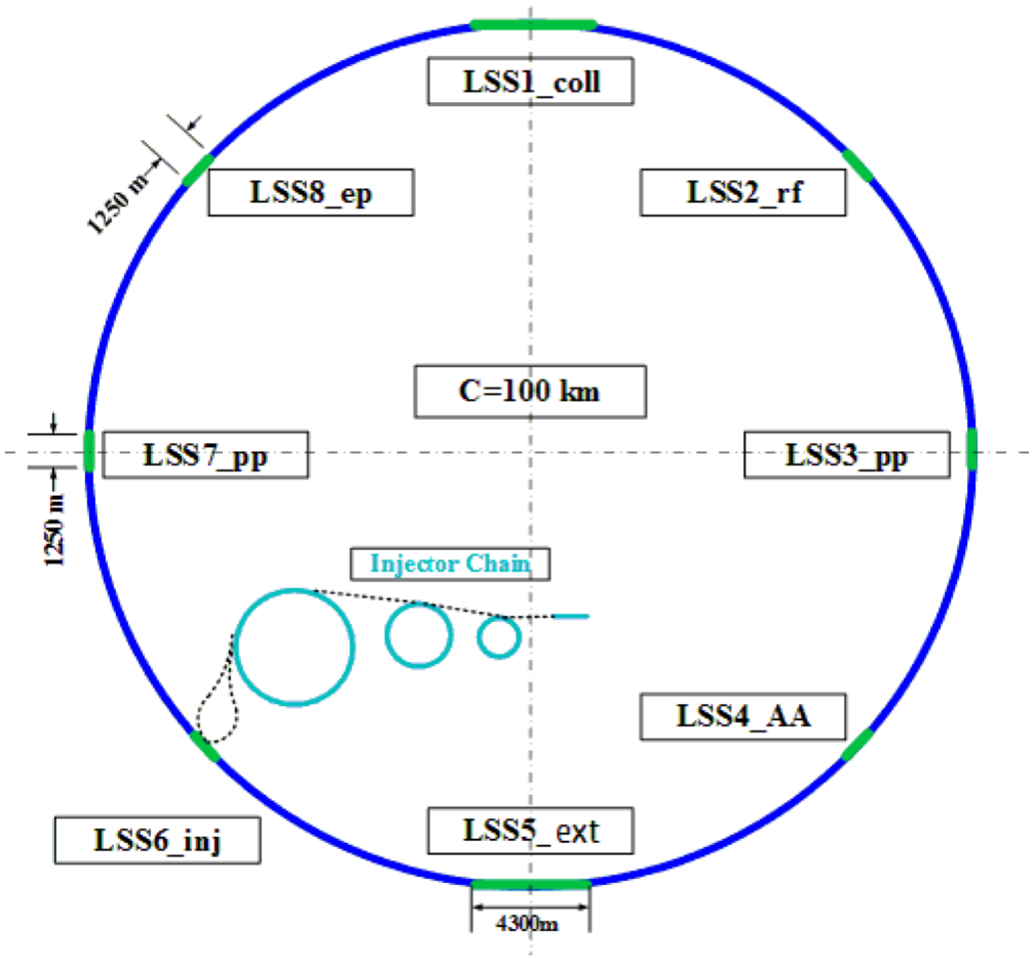
Proposed Higher-Energy Hadron Colliders

Snowmass '21

FCC-hh

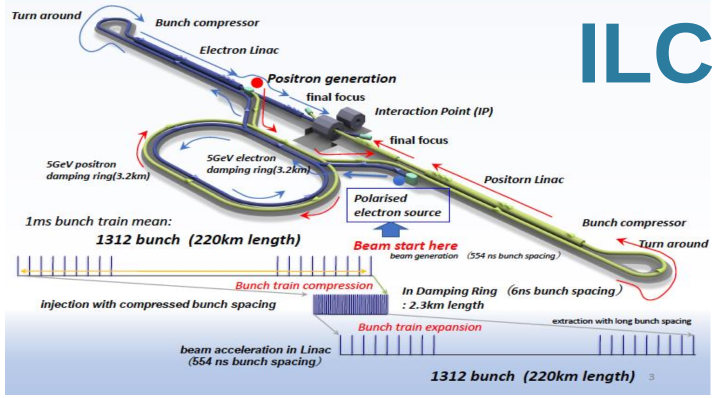


SPPC

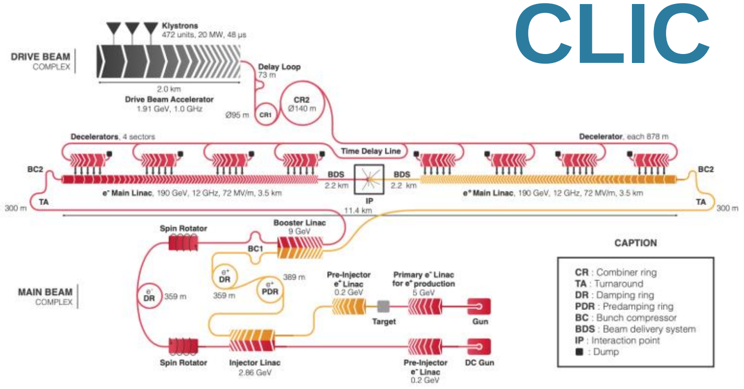


Proposed e⁺e⁻ Higgs & EW Factories

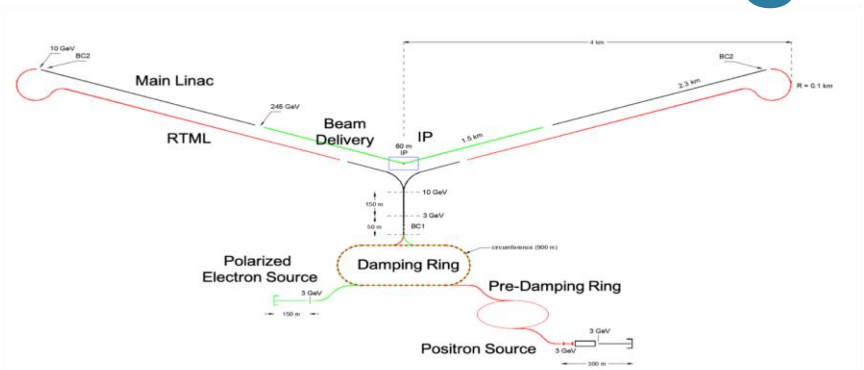
ILC



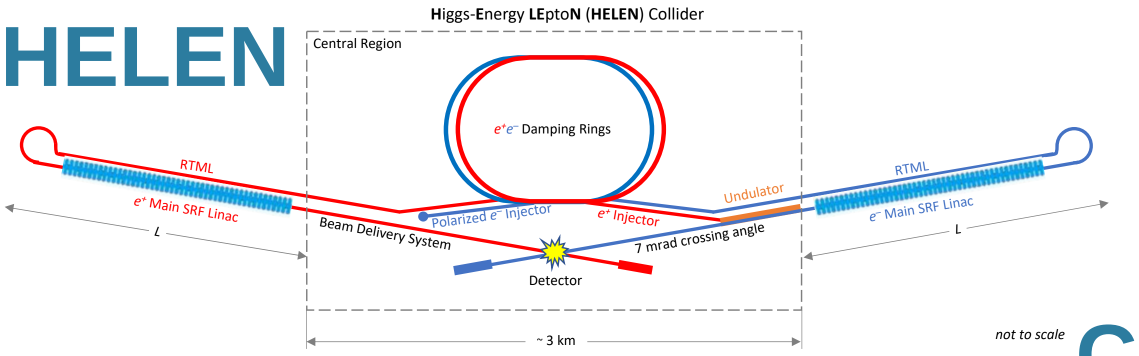
CLIC



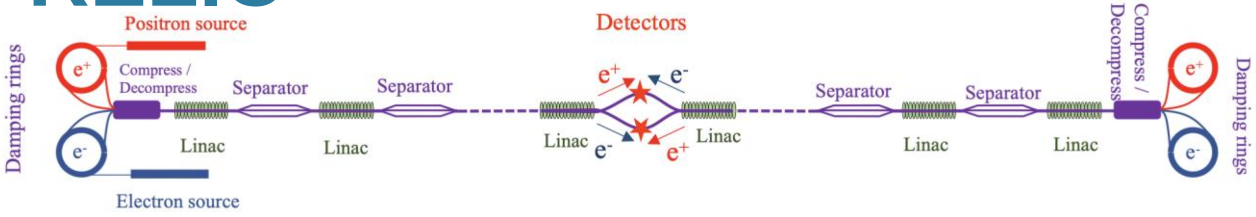
C³



HELEN

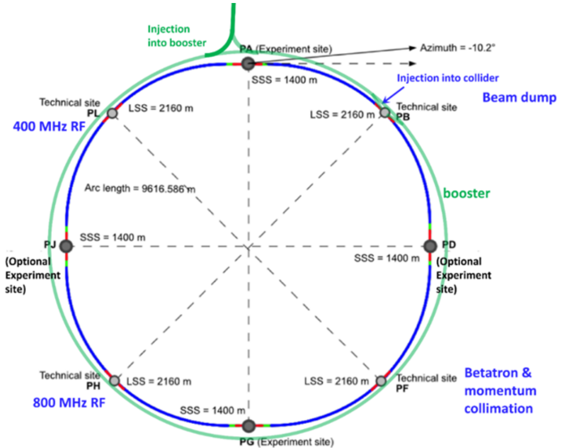


RELIC

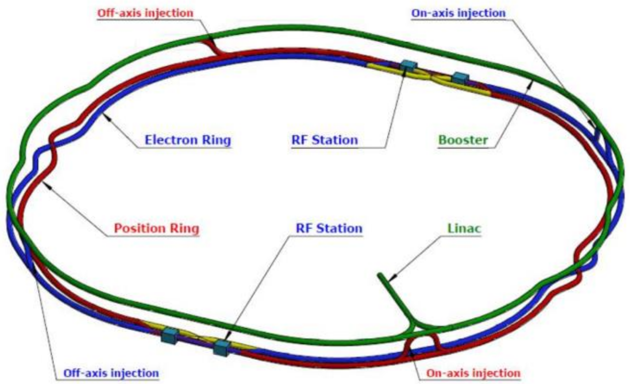


not to scale

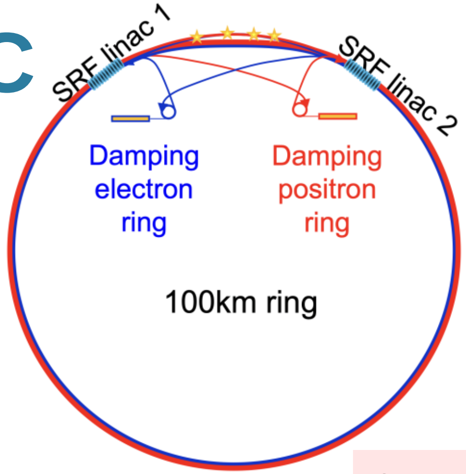
FCC-ee



CEPC



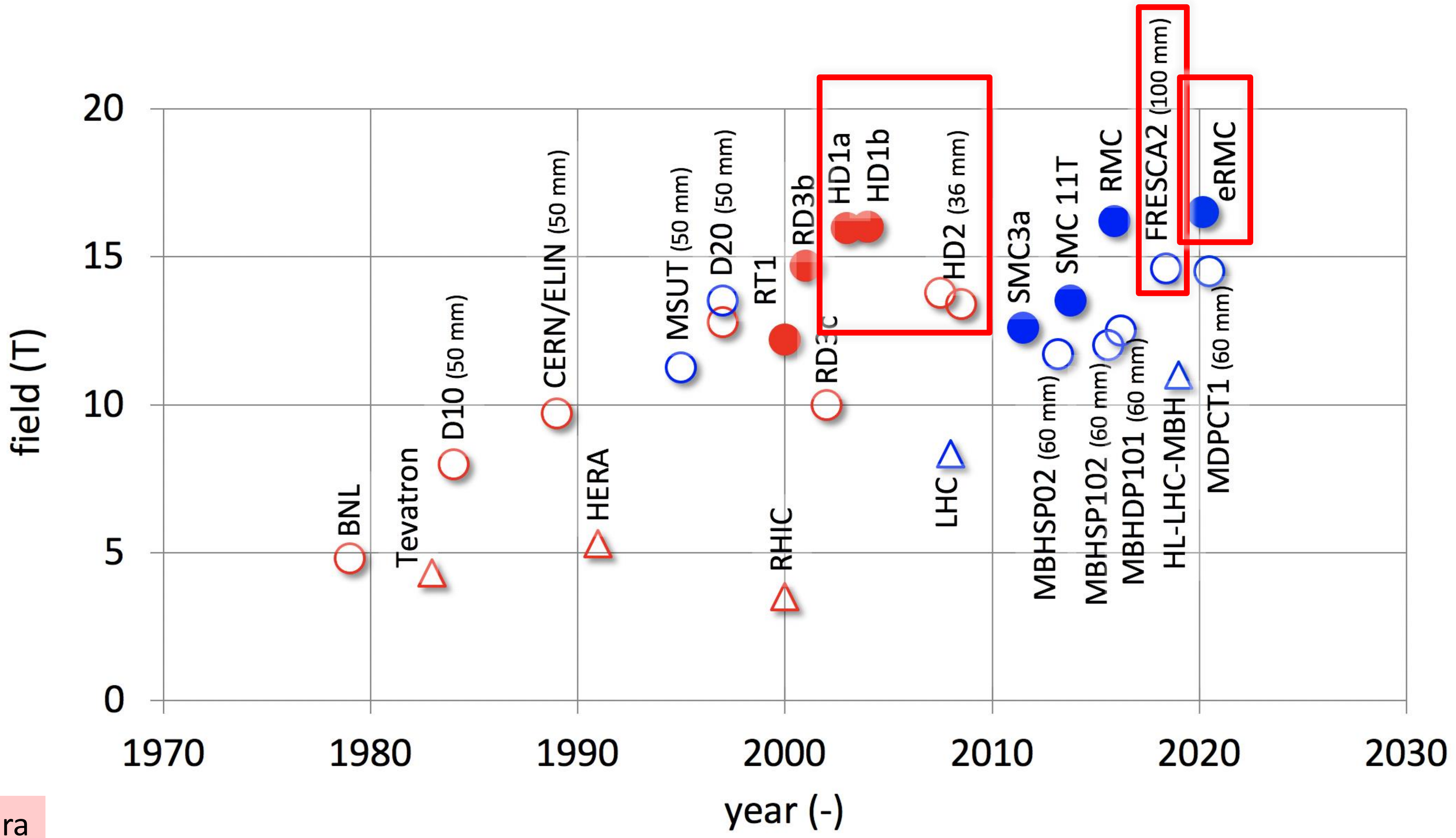
CERC



Towards the next, next-next and next-next-next generation of accelerators – main themes

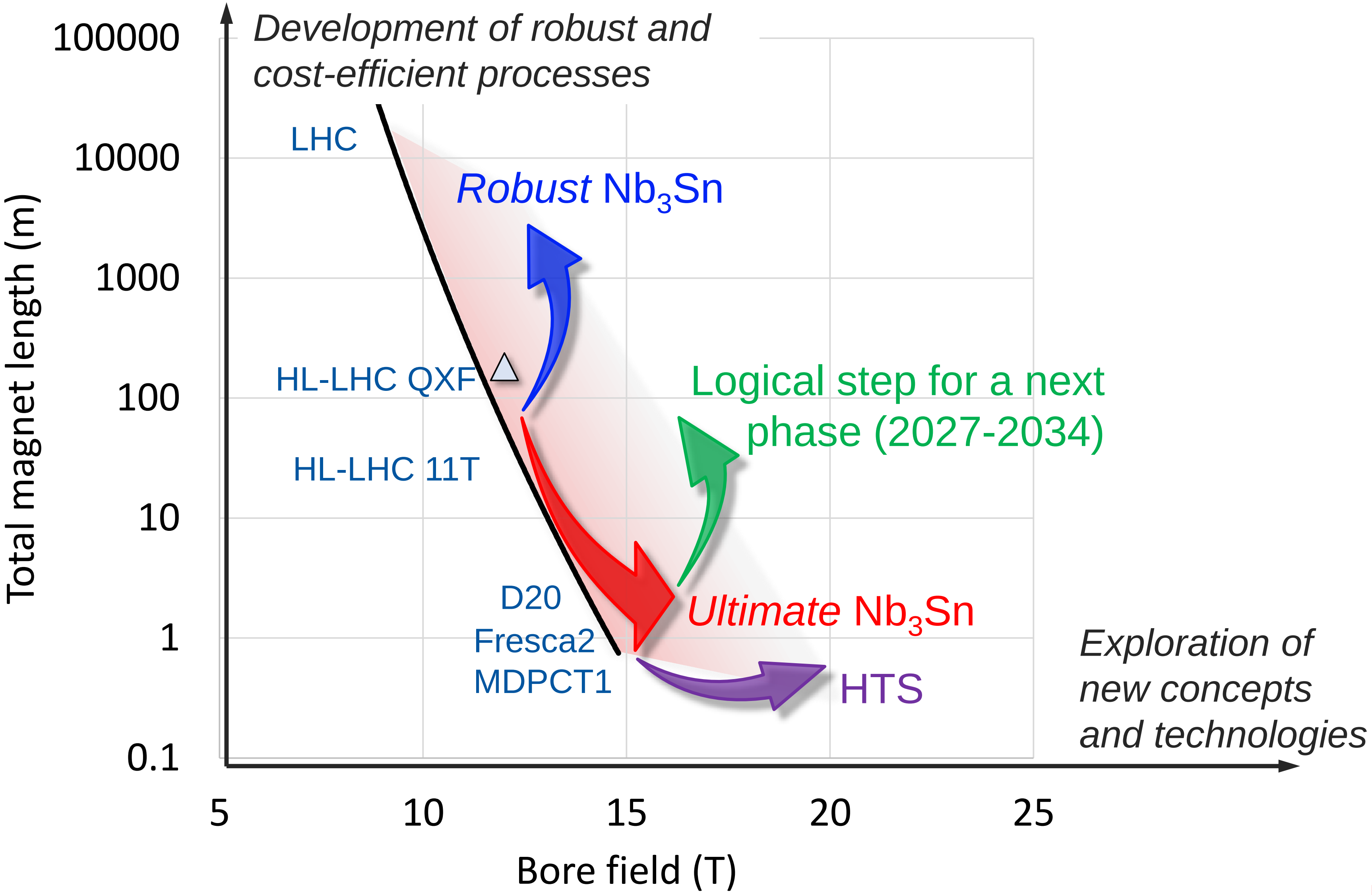
- High-field magnets
- SC Radiofrequency systems
- Efficient RF power sources
- e^+ production
- Gamma Factory
- Monochromatization
- Energy Recovery Linacs
- $\gamma\gamma$ colliders
- Muon Collider(s)
- Advanced Accelerator Concepts
- Sustainability

High-Field Magnet – historical progress



Luca Bottura

CERN High-Field Magnet Program

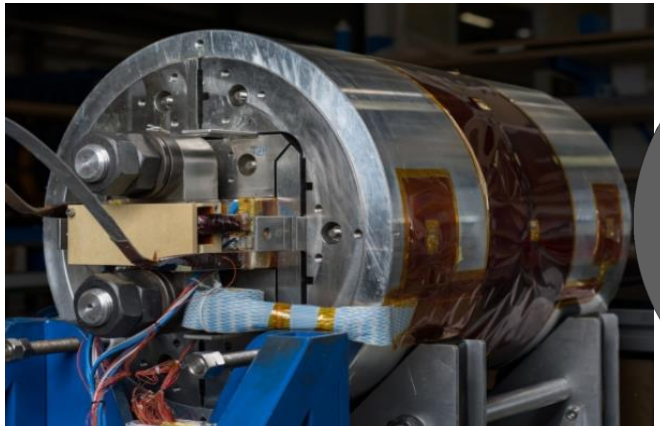
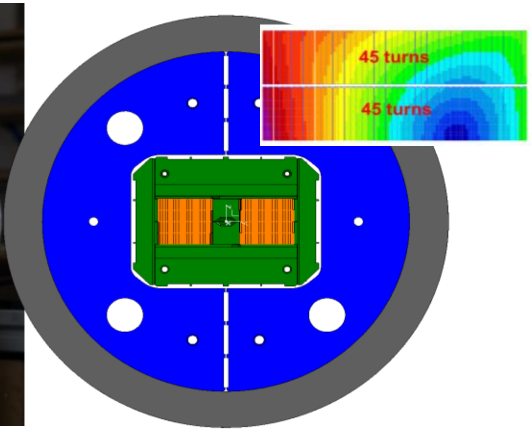


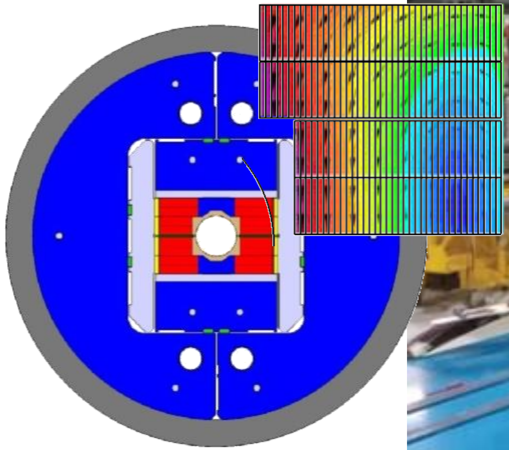
Luca Bottura

High-Field Nb_3Sn Magnets

CERN

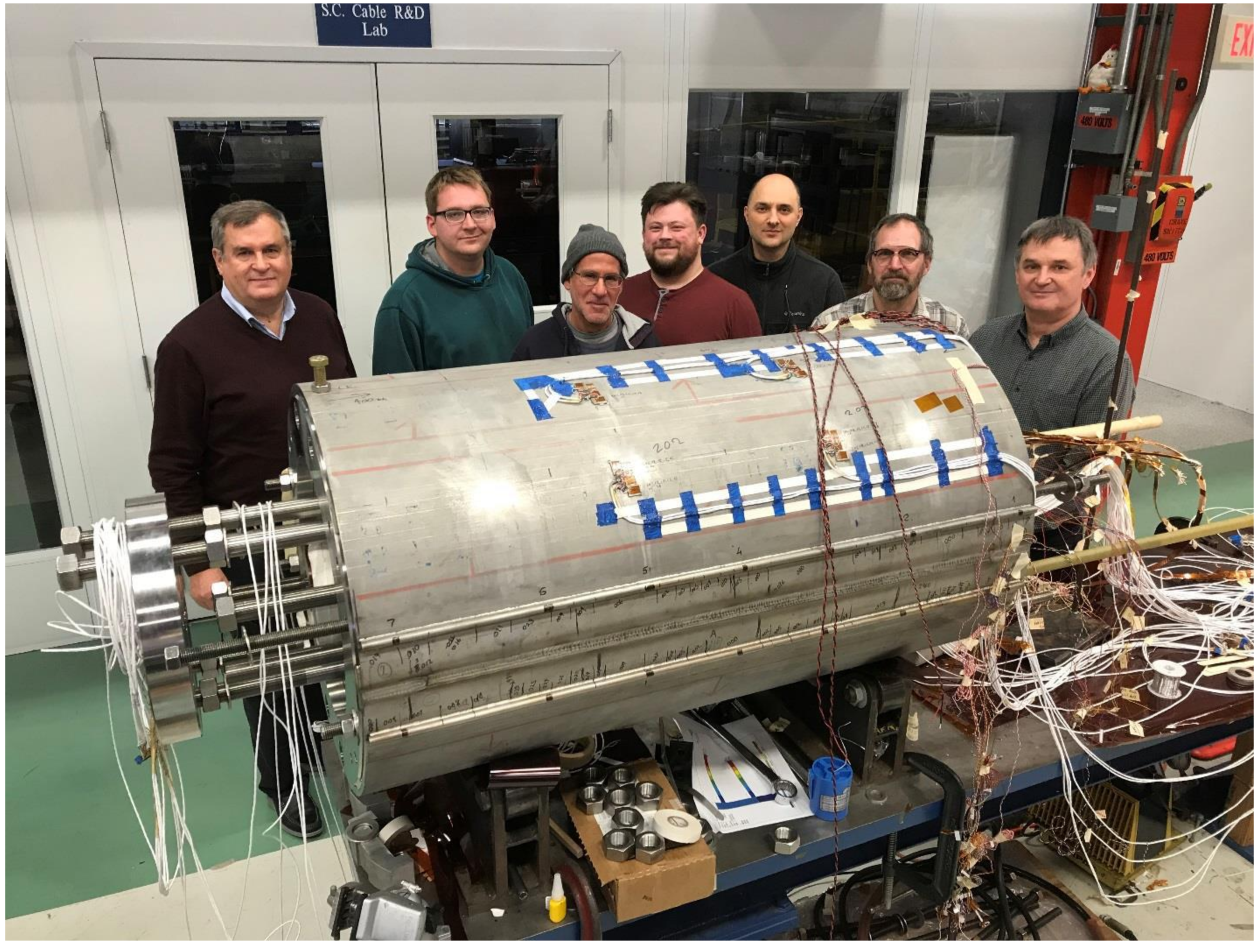
RMC/eRMC (2-decks, no aperture), 16.5 T




FRESCA2 (4-decks, 100 mm), 14.6 T

FNAL



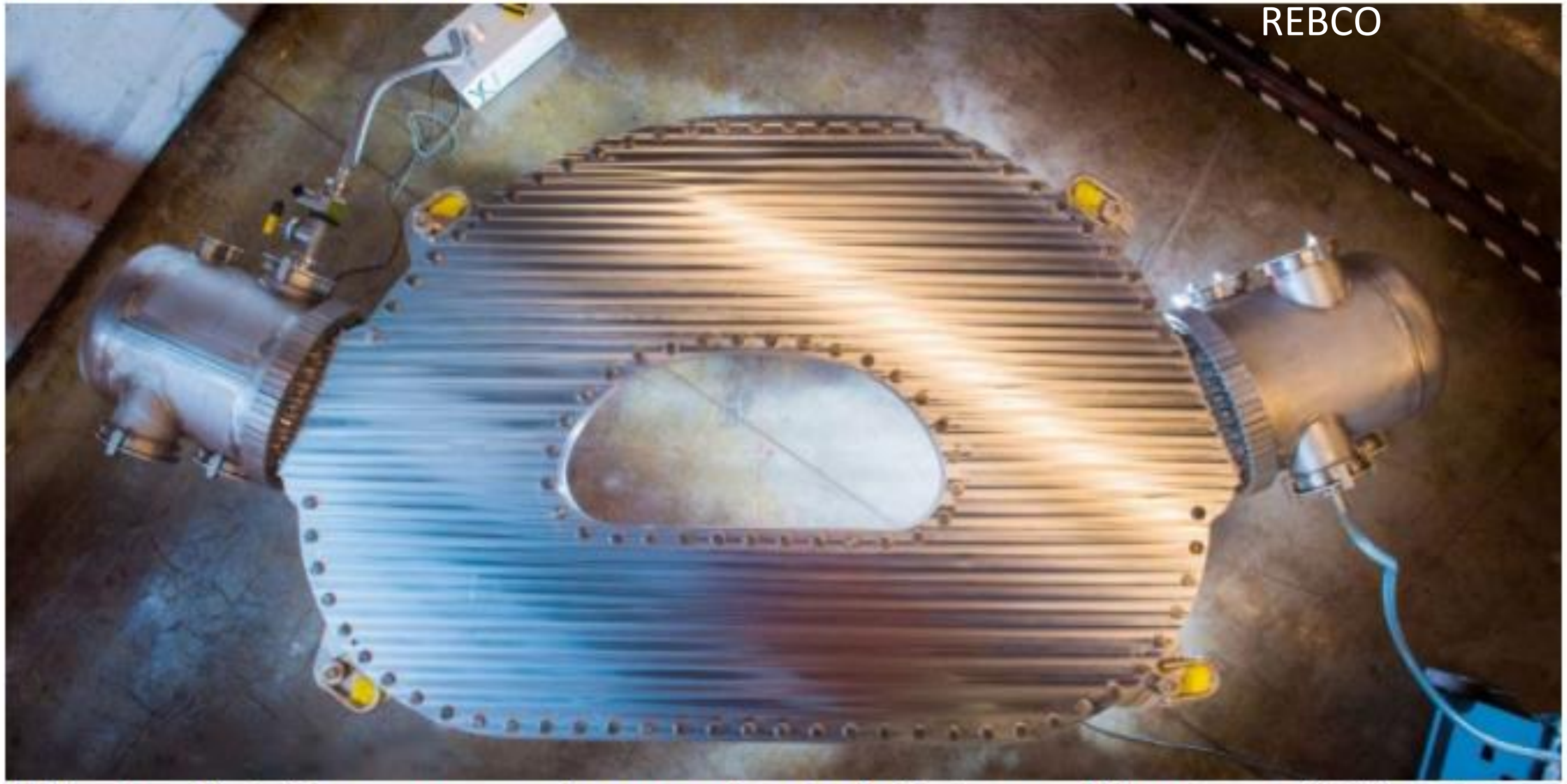
MDPCT1 (4-layer graded coil, 60 mm), 14.5 T

Nuclear Fusion HTS Magnet Progress

RESEARCH & APPLICATIONS

MIT ramps 10-ton magnet up to 20 tesla in proof of concept for commercial fusion

Fri, Sep 10, 2021, 6:59PM | Nuclear News



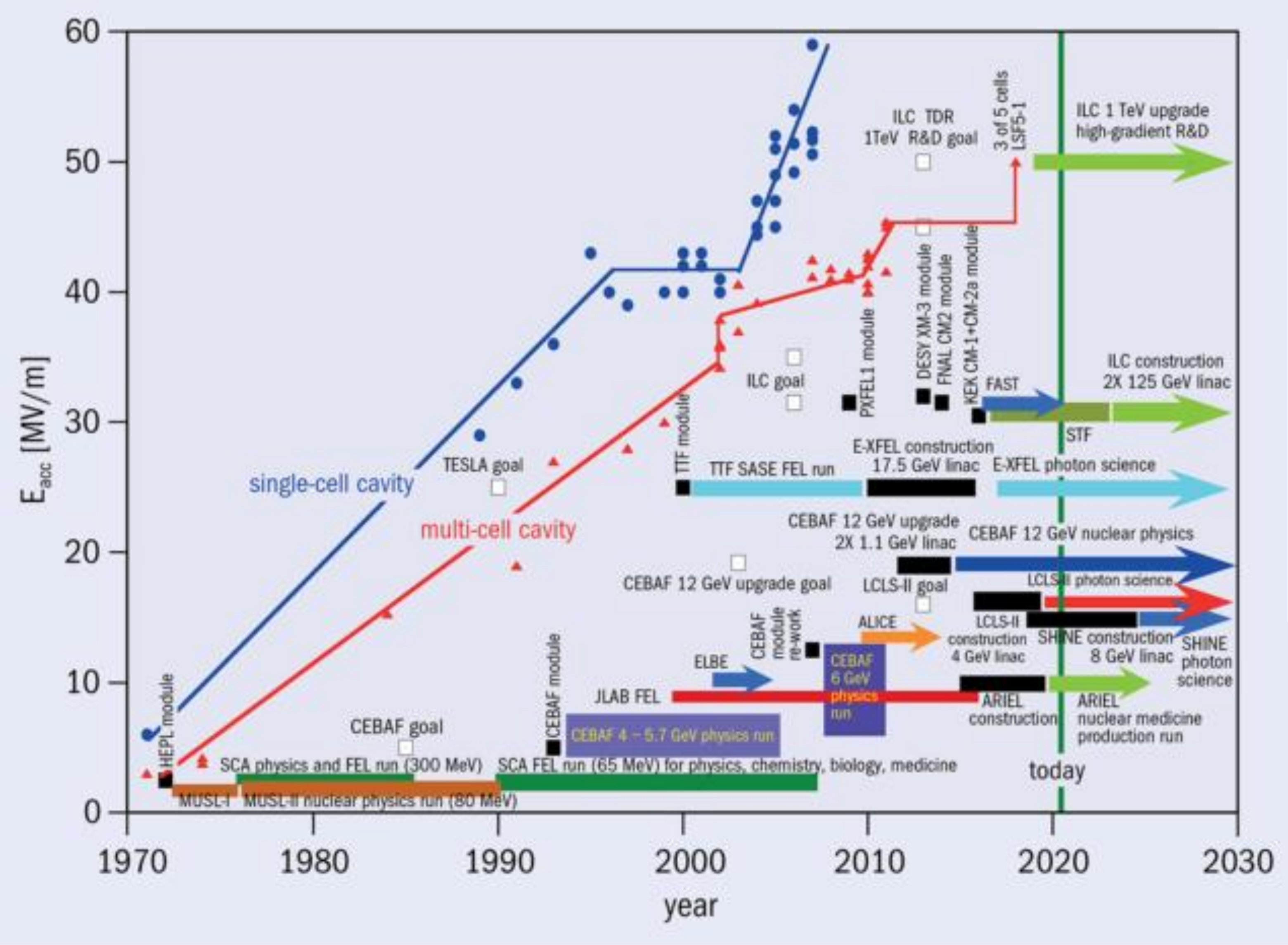
This large-bore, full-scale high-temperature superconducting magnet designed and built by Commonwealth Fusion Systems and MIT's Plasma Science and Fusion Center is the strongest fusion magnet in the world. (Photo: Gretchen Ertl, CFS/MIT-PSFC)

September 2021

toroidal model coil

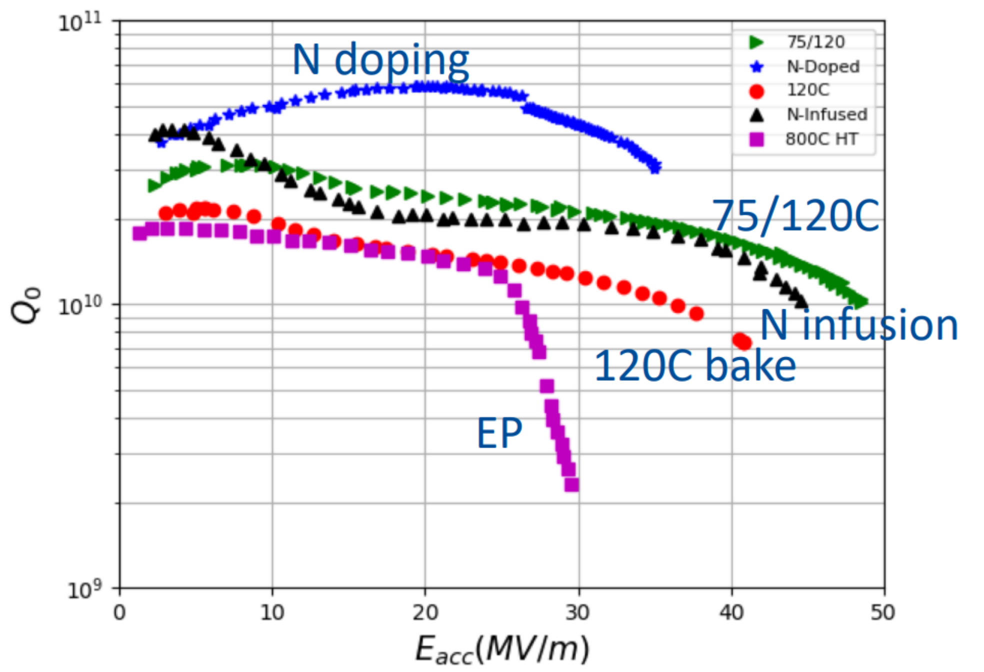
synergies with accelerator magnet developments

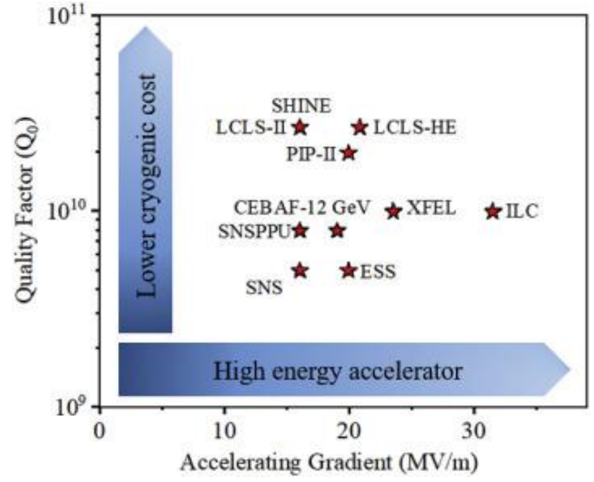
SC Radiofrequency Systems



Gradient growth SRF linac accelerating gradient achievements and application specifications since 1970 (CERN Courier., Nov. 2020)

Anna Grasselino

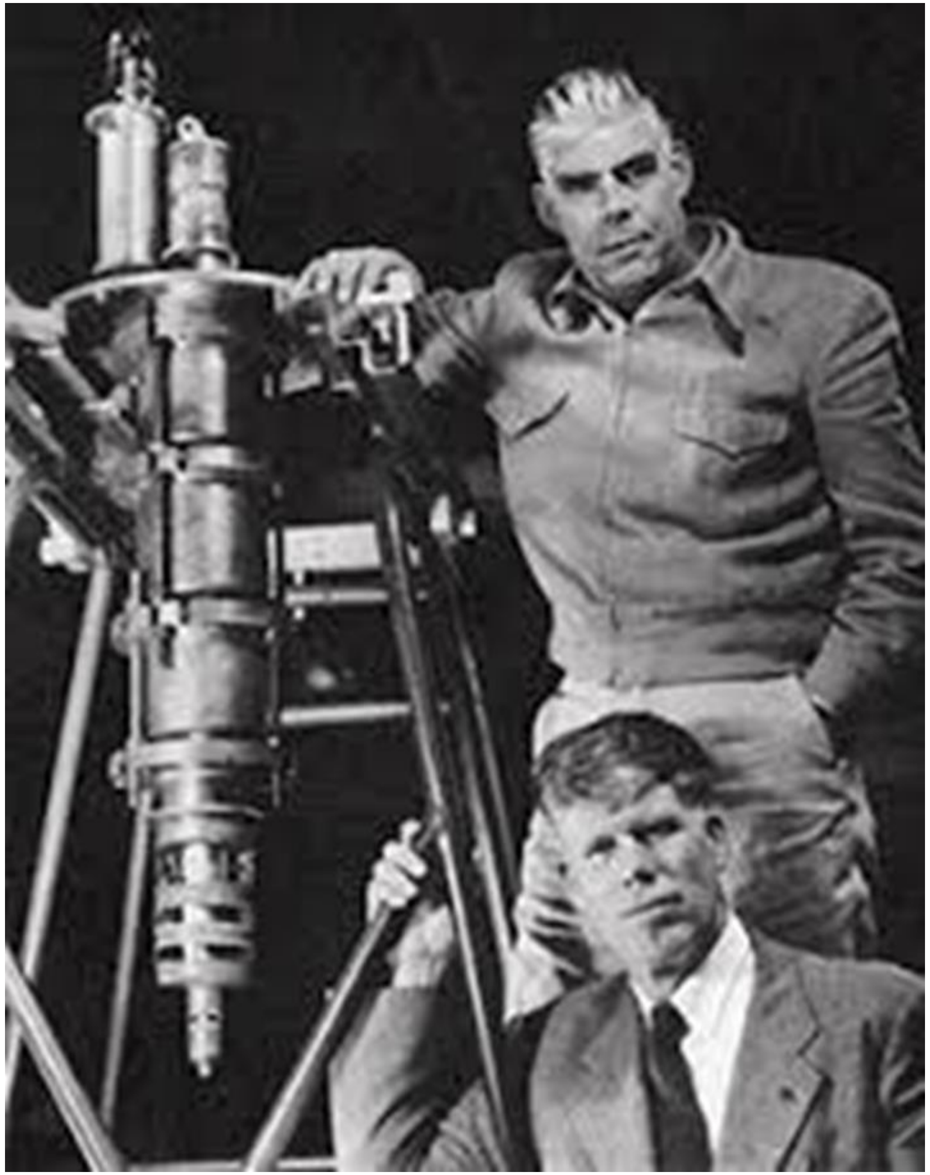




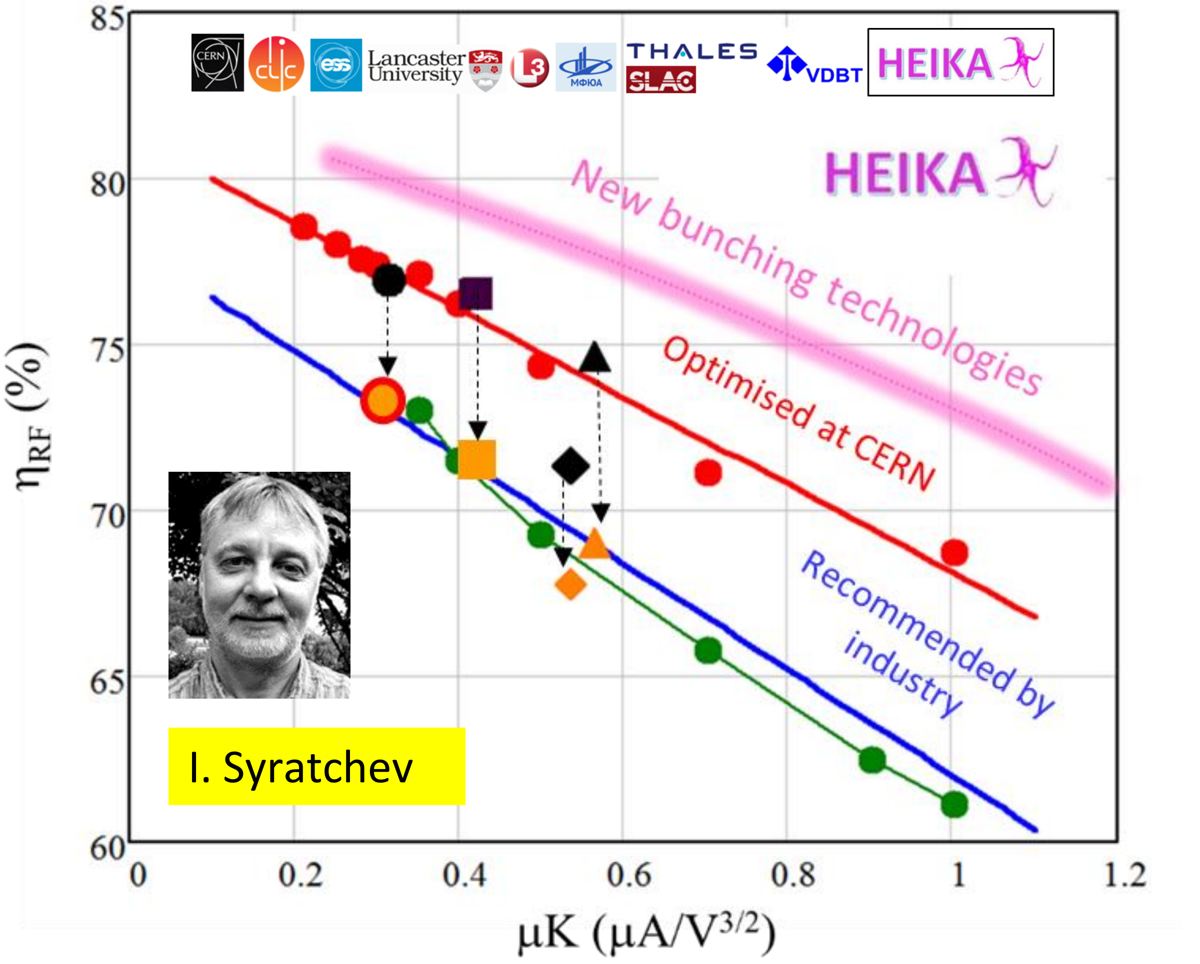
P. Dhakal

More Efficient RF Power Sources

1937: the Varian brothers of Palo Alto invent the klystron



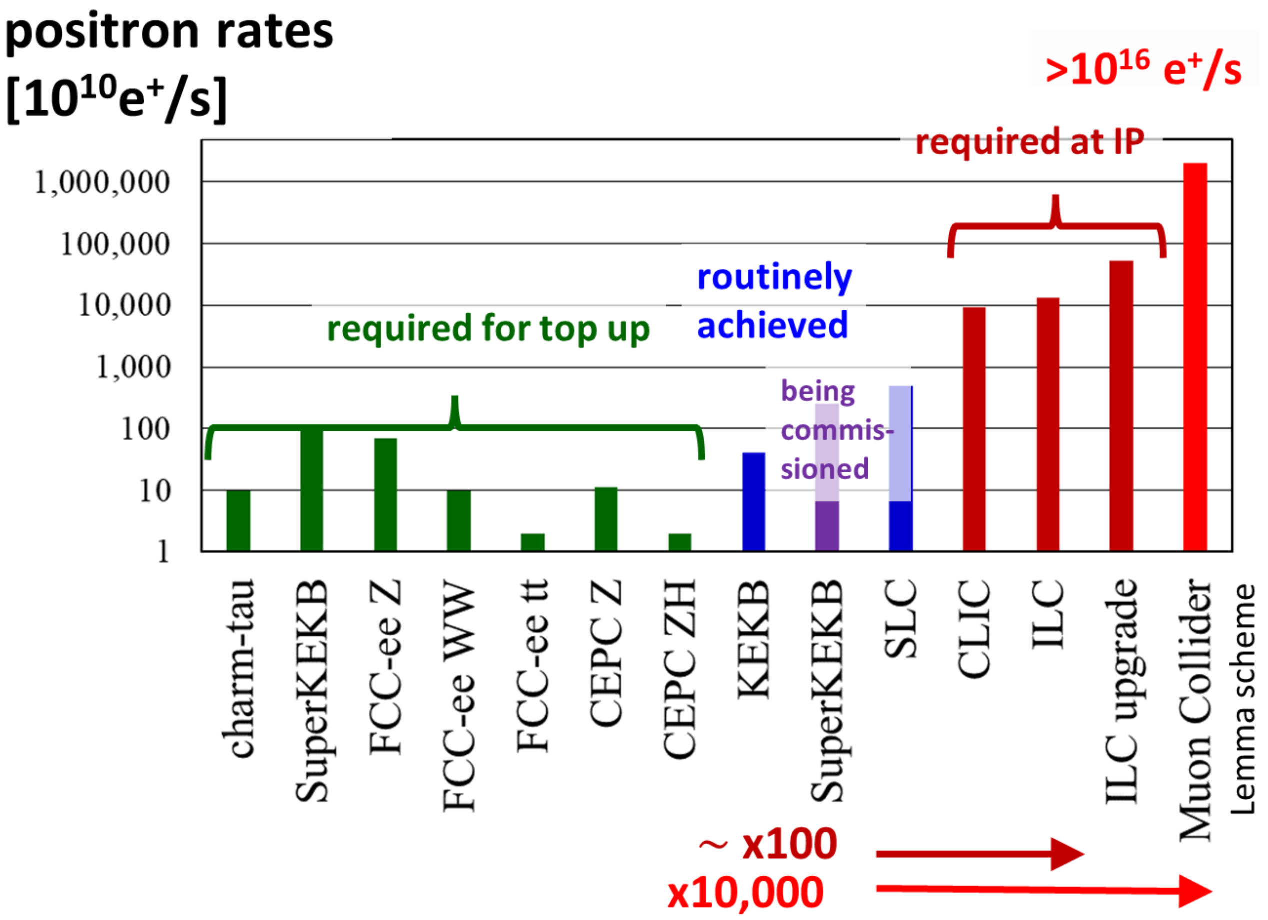
80 years later, another breakthrough in klystron technology



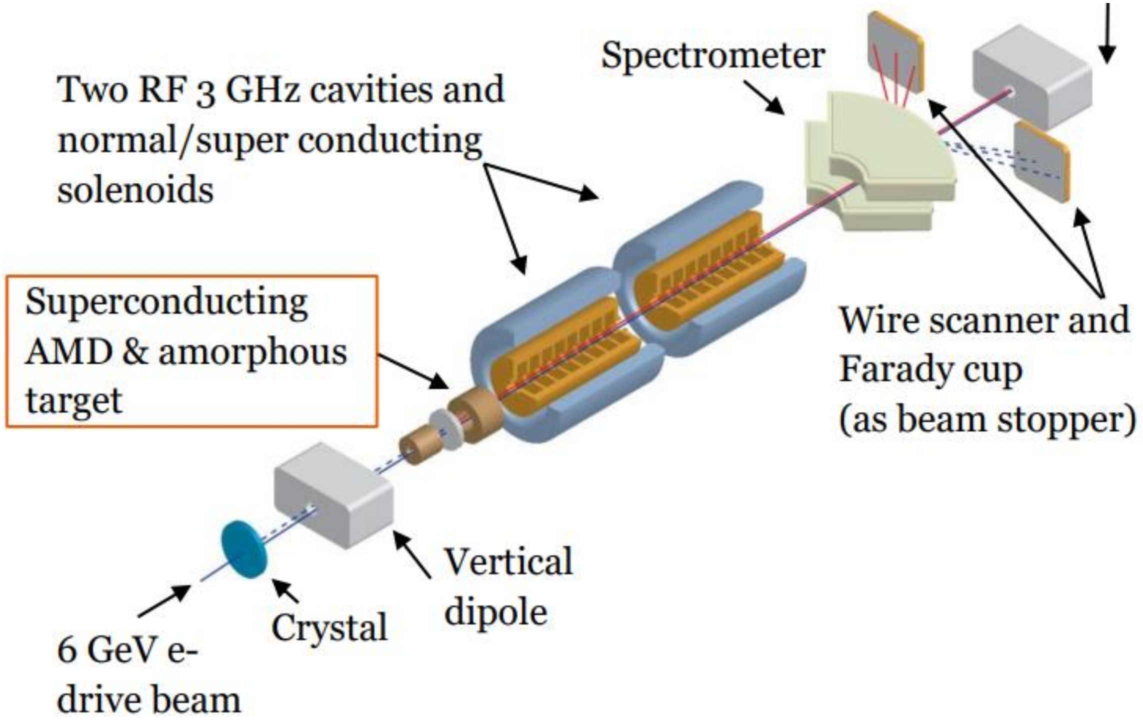
New bunching technologies

Positron Production

Challenging demands



Innovative high-yield source



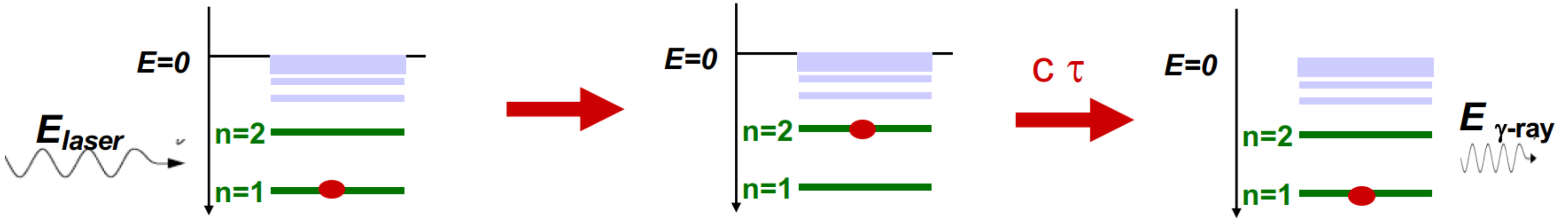
P^3: PSI e^+ production experiment with HTS solenoid at SwissFEL

planned for 2024/25

Gamma Factory concept

Witek Krasny

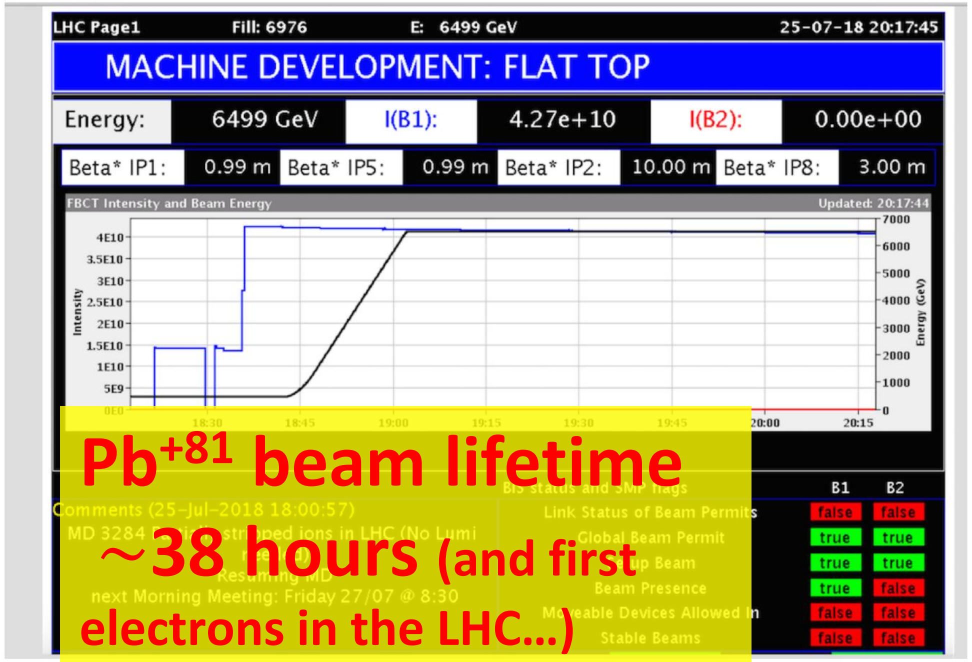
arXiv:1511.07794



partially stripped heavy-ion beam in LHC (or FCC): resonant scattering of laser photons off ultrarelativistic atomic beam; high-stability laser-light-frequency converter

$$\nu^{max} \longrightarrow (4\,\gamma_L^2)\ \nu_{Laser}$$

Gamma Factory proof-of-principle experiment in the LHC

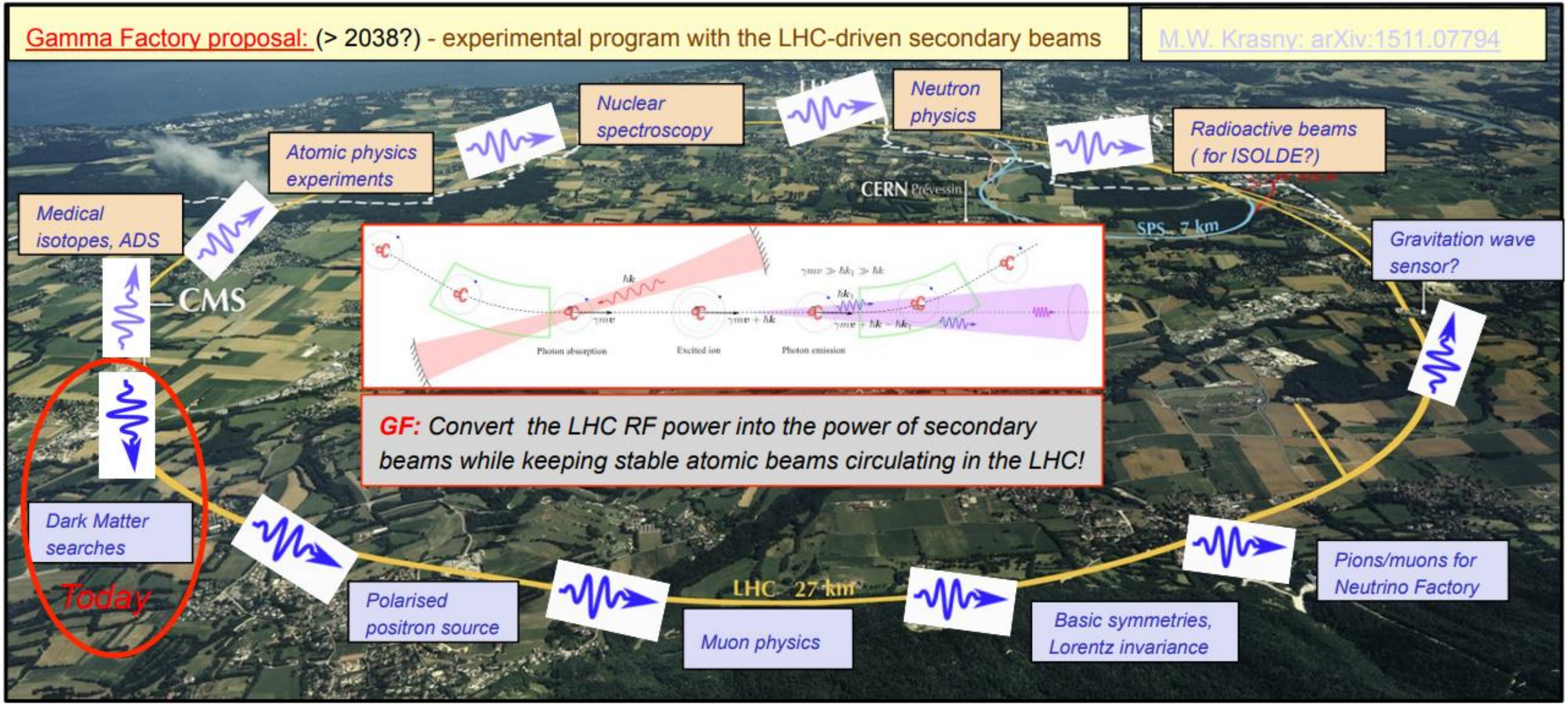


Pb^{+81} beam lifetime ~38 hours (and first electrons in the LHC…)

proposed applications:

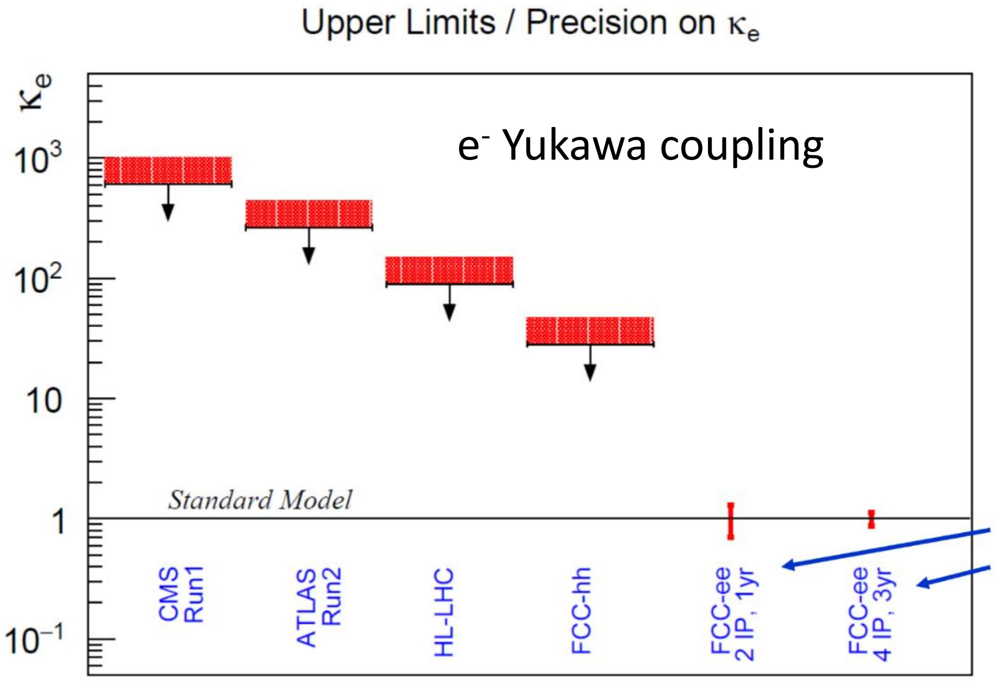
- intense source of e^+ (10^{16}-10^{17}/s), π, μ etc
- doppler laser cooling of high-energy beams
- HL-LHC w. laser-cooled isocalar ion beams

The LHC as a driver of secondary beams



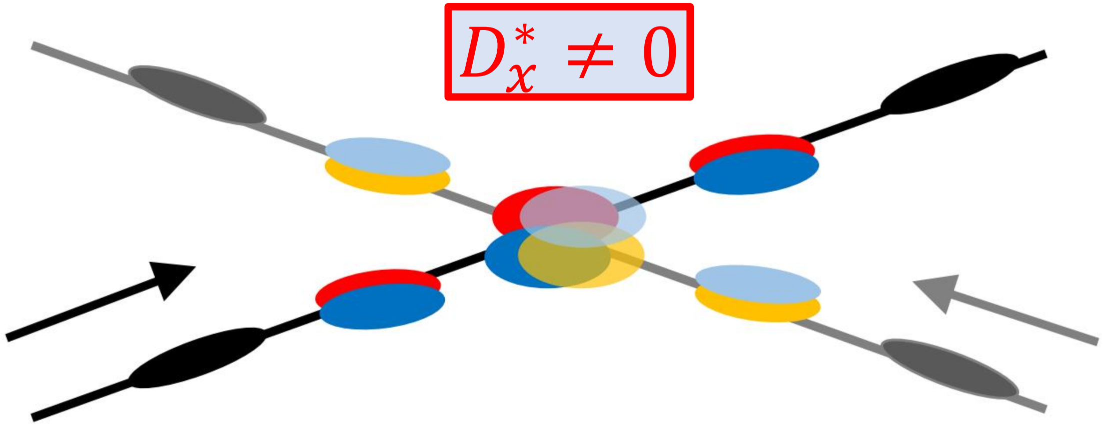
Schematic transformation of the LHC into a Gamma-Factory-based driver of secondary beams [Witek Krasny].

Monochromatization Schemes

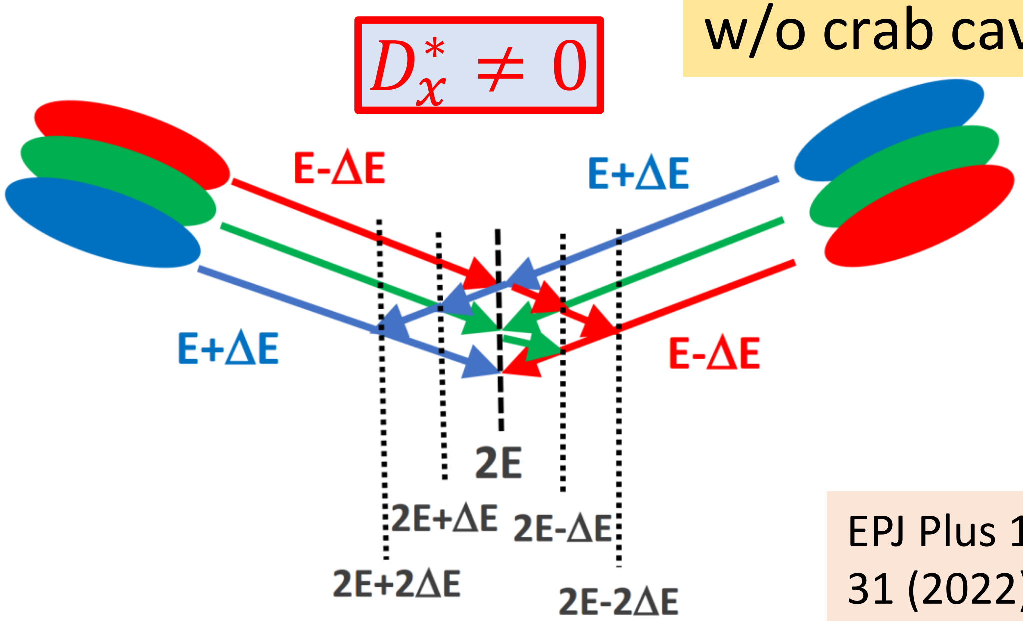


nonvanishing IP dispersion

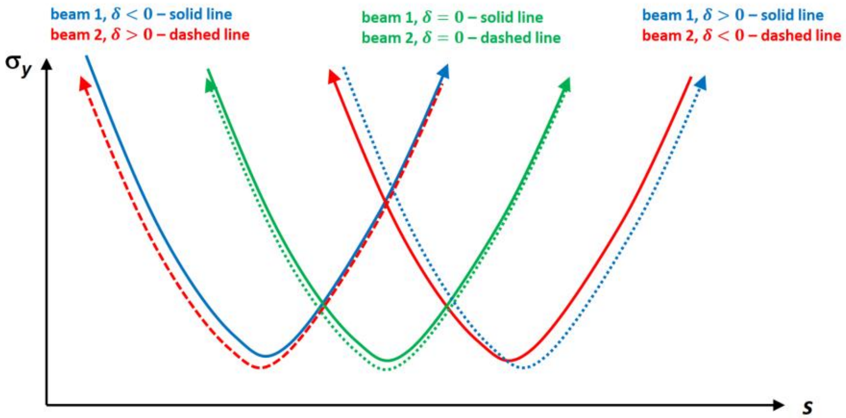
w crab cavities



w/o crab cavities



chromatic waist shift

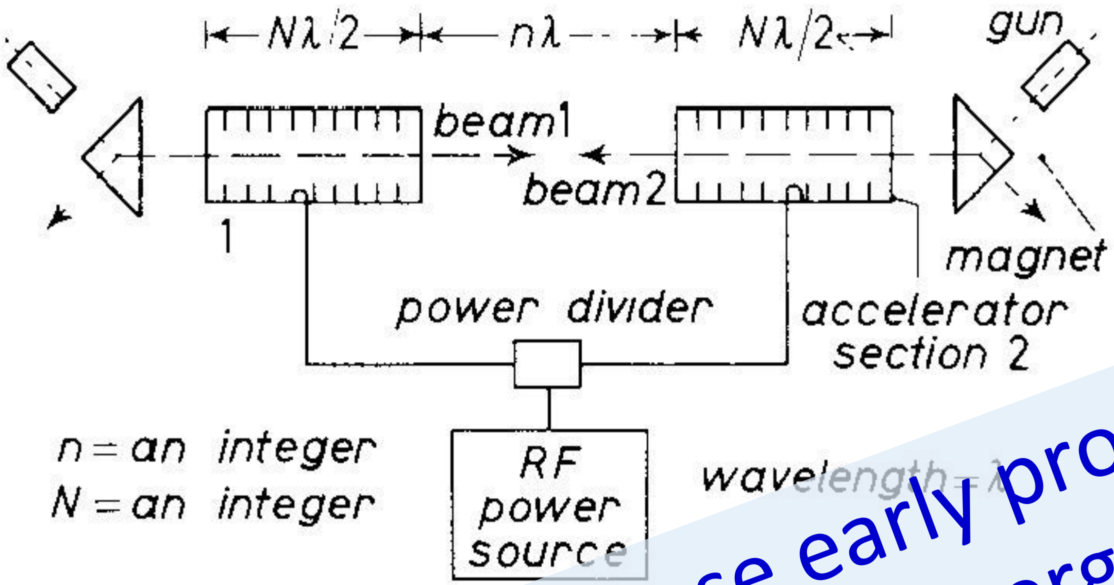


Pantaleo Raimondi

EPJ Plus 137, 31 (2022)

Energy Recovery Linacs - Historical Proposals 1960s & 70s

early linear-collider proposals

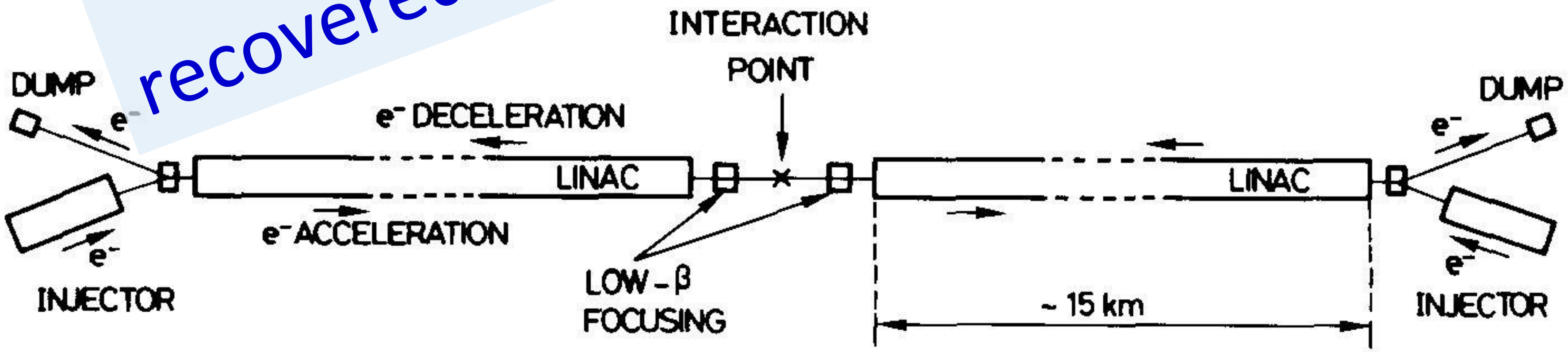


1-6 GeV c.m.

Maury Tigner, *"A Possible Apparatus for Clashing-Beam Experiments"*, Nuovo Cimento 37, 1228 (**1965**)

these early proposal always recovered the energy of the spent beam!

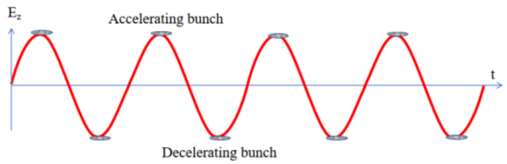
Ugo Amaldi, *"A possible scheme to obtain e-e- and e+e- collisions at energies of hundreds of GeV"*, Physics Letters B61, 313 (**1976**)



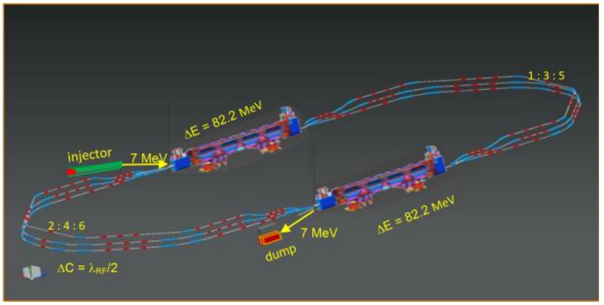
300 GeV c.m.

Energy Recovery Linacs : Revival since 2019

European LDG roadmap

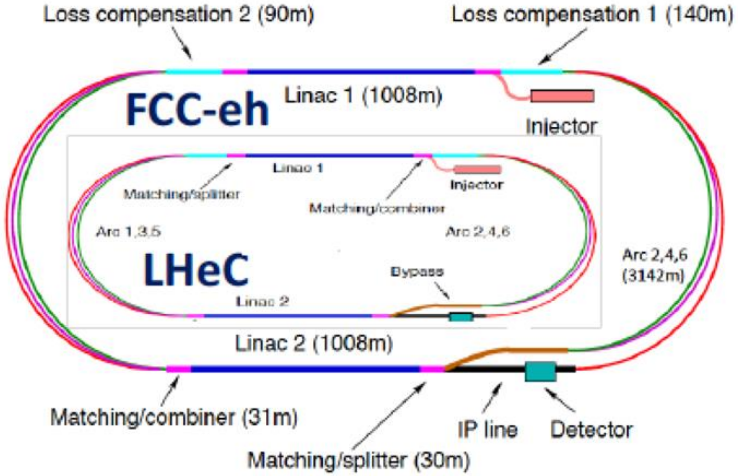


V. Litvinenko et al.



test Facility PERLE at IJClab (high current, multi-turn) to complement MESA, CBETA, bERLinPRO & EIC cooler

Energy Frontier Collider Applications of Energy Recovery Linacs

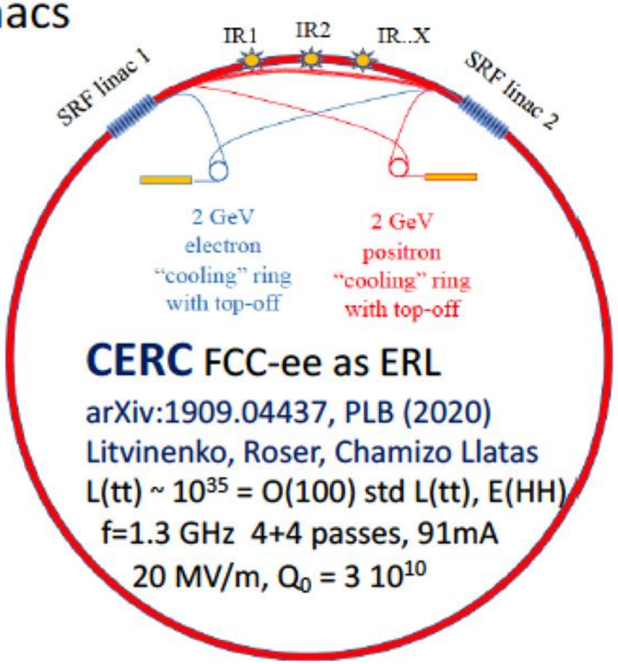


sqrt(s_{ep}) = 1-4 TeV

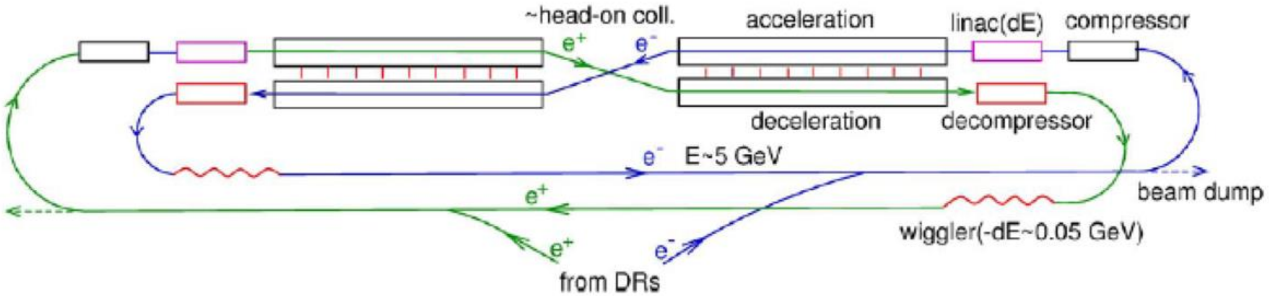
L(HERA) x 1000
(ERL and LHC)

1206.2913, JPhysG
2007.14491, JPhysG

f=802Mz,
3+3 passes: 20mA x 6
20 MV/m, $Q_0 > 10^{10}$



CERC FCC-ee as ERL
arXiv:1909.04437, PLB (2020)
Litvinenko, Roser, Chamizo Llatas
L(tt) ~ 10^{35} = O(100) std L(tt), E(HH)
f=1.3 GHz 4+4 passes, 91mA
20 MV/m, $Q_0 = 3\ 10^{10}$



ERLC ILC as ERL
V. Telnov at LCWS → arXiv:2105.11015
L(ERLC) ~ 10^{36} = O(100) std L(ILC)
This yields O(10^7) HZ events in 3 years.
1+1 passes, l =160m
f=750 MHz, 20 MV/m, $Q_0 > 10^{10}$

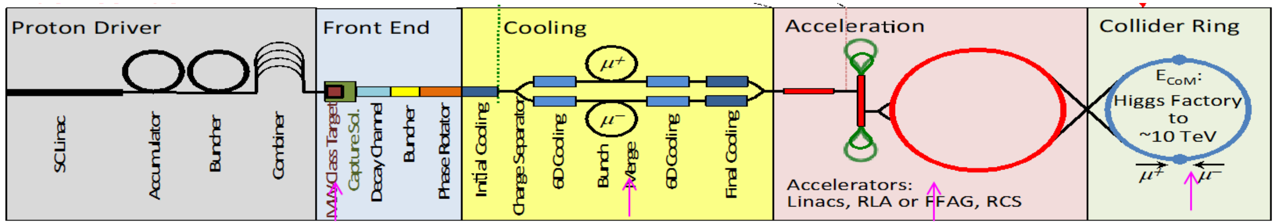
Main advances: flat instead of round beams, much smaller (vertical) beam sizes, higher beam current → ~10,000x higher luminosity

Muon Colliders

~1.6×10^9 x less SR than e^+e^-, no beamstrahlung problem

two production schemes proposed

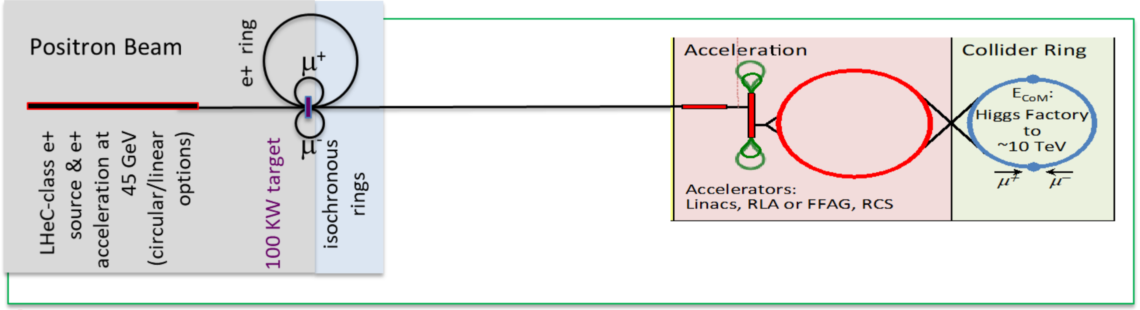
US-MAP (2015) *p*-driven



key challenges

$\sim 10^{13}$-10^{14} μ / sec tertiary particle $p \to \pi \to \mu$:	fast cooling ($\tau = 2\mu s$) by 10^6 (6D)	fast acceleration mitigating μ decay	background from μ decay

Italian LEMMA (2017) e^+-annihilation



key challenges: $\sim 10^{11}$ μ / sec from $e^+e^- \to \mu^+\mu^-$

key R&D: 10^{15} e^+/sec, 100 kW class target, NON destructive process in e+ ring

needs large 45 GeV e^+ ring like FCC-ee, possible upgrade path to **FCC-μμ**

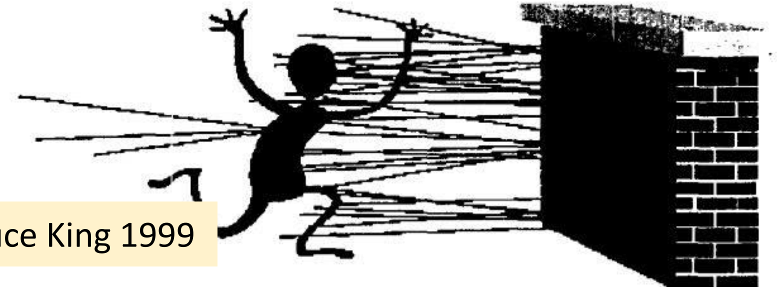
μ's decay within a few 100 - 1000 turns:

→ rapid acceleration

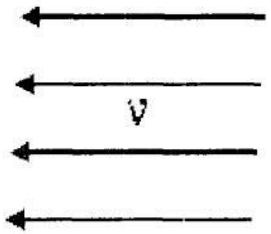
(perhaps plasma?)

→ ν radiation hazard

(limits maximum μ energy)



Bruce King 1999



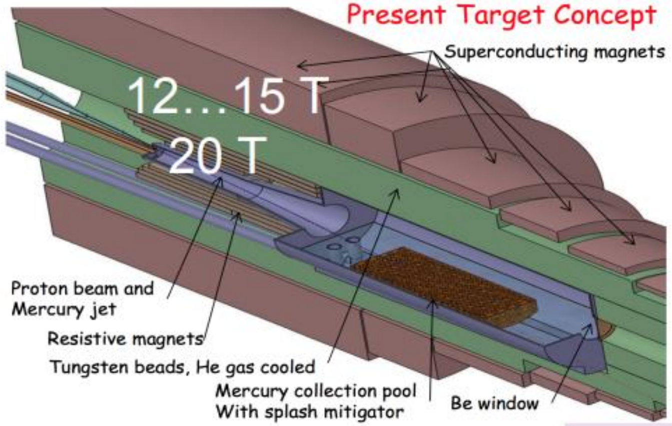
$\sigma_\nu \propto E$, **flux** $\propto E^2$ (Lorentz boost)

solution beyond 10 TeV unclear

Muon Colliders – Example Challenges

target design for *p* driven μ collider

MAP target design, K. McDonald, et al.



Two approaches:
- 15 T outer superconducting + 5 T inner resistive solenoid
- O(20 T) HTS solenoid

Shield superconducting solenoid
⇒ larger aperture
Synergy with ITER

A. Lechner et al.
L. Bottura et al.

Shock in target: Simulations of graphite target indicate 2 MW could be acceptable

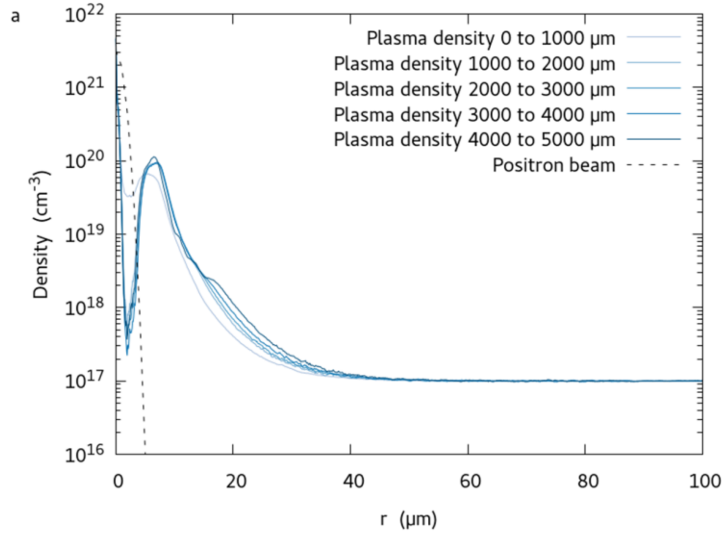
STFC will also study alternatives

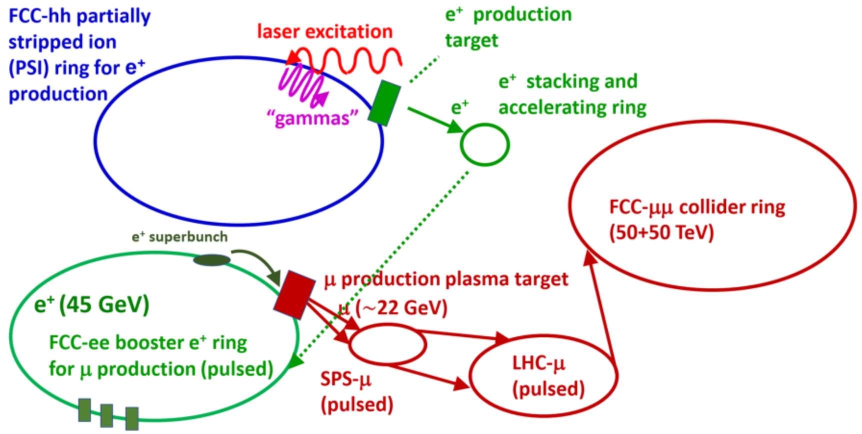
Rui Franqueira Ximenes et al.

Proton beam

Operation at 2000 °C to maximise stress resistance

plasma target for e^+ driven μ collider



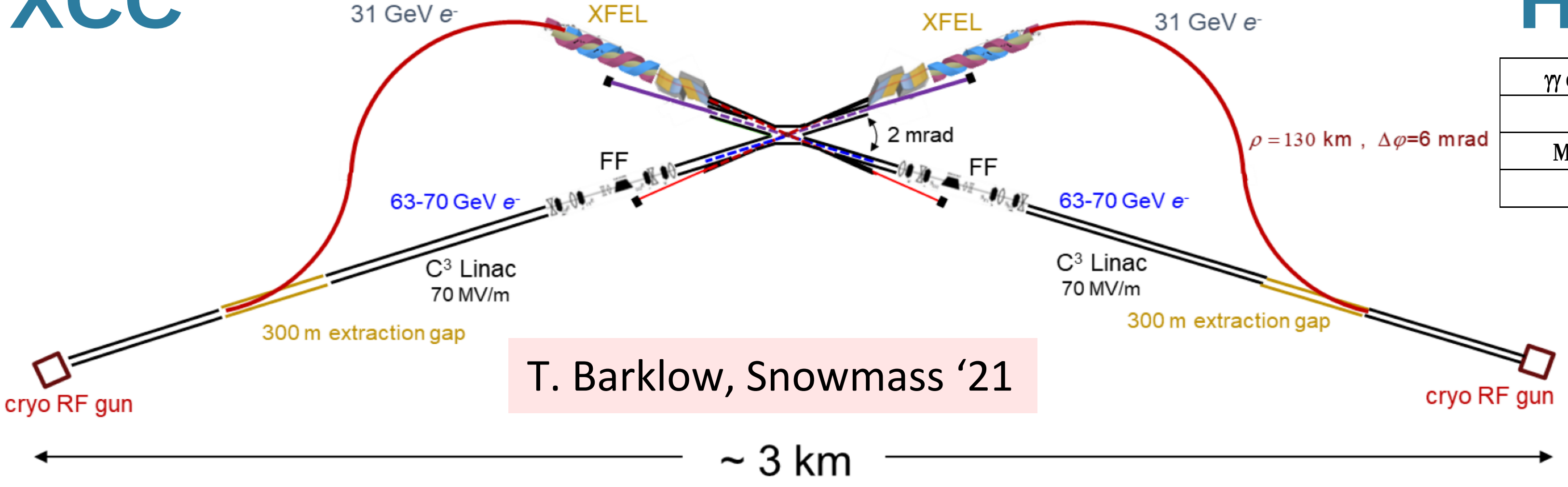


D. Schulte, IPAC'22

J. Farmer et al., IPAC'22

$\gamma\gamma$ colliders

XCC



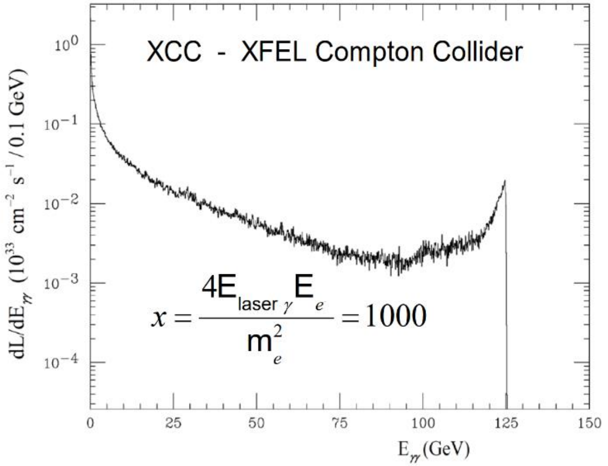
T. Barklow, Snowmass '21

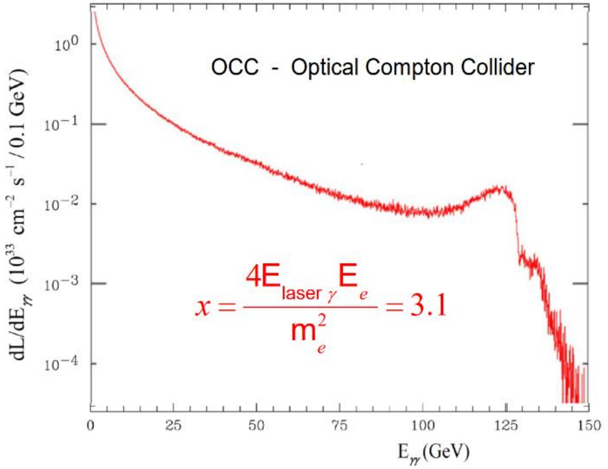
Final Focus parameters	Approx. value	XFEL parameters	Approx. value
Electron energy	62.8 GeV	Electron energy	31 GeV
Electron beam power	0.57 MW	Electron beam power	0.28 MW
β_x/β_y	0.03/0.03 mm	normalized emittance	120 nm
$\gamma\epsilon_x/\gamma\epsilon_y$	120/120 nm	RMS energy spread $\langle\Delta\gamma/\gamma\rangle$	0.05%
σ_x/σ_y at e^-e^- IP	5.4/5.4 nm	bunch charge	1 nC
σ_z	20 μm	Linac-to-XFEL curvature radius	133 km
bunch charge	1 nC	Undulator B field	$\gtrsim 1$ T
Rep. Rate at IP	240×38 Hz	Undulator period λ_u	9 cm
σ_x/σ_y at IPC	12.1/12.12 nm	Average β function	12 m
$\mathcal{L}_{\text{geometric}}$	9.7×10^{34} cm^2 s^{-1}	x-ray λ (energy)	1.2 nm (1 keV)
δ_E/E	0.05%	x-ray pulse energy	0.7 J
L^* (QD0 exit to e^- IP)	1.5m	pulse length	40 μm
d_{cp} (IPC to IP)	60 μm	$a_{\gamma x}/a_{\gamma y}$ (x/y waist)	21.2/21.2 nm
QD0 aperture	9 cm diameter	non-linear QED ξ^2	0.10
Site parameters	Approx. value		
crossing angle	2 mrad		
total site power	85 MW		
total length	3.0 km		

HE - HL $\gamma\gamma$ Collider

$\gamma\gamma$ collider parameters	0.5 TeV	1.0 TeV	3.0 TeV	10 TeV	Units
x-factor	2 (4)	4	12	40	
Max. photon energy	0.17 (0.20)	0.40	1.38	4.88	TeV
$L_{\gamma\gamma}$ / L_{ee}	≤ 10	≤ 10	≤ 6	≤ 3	%

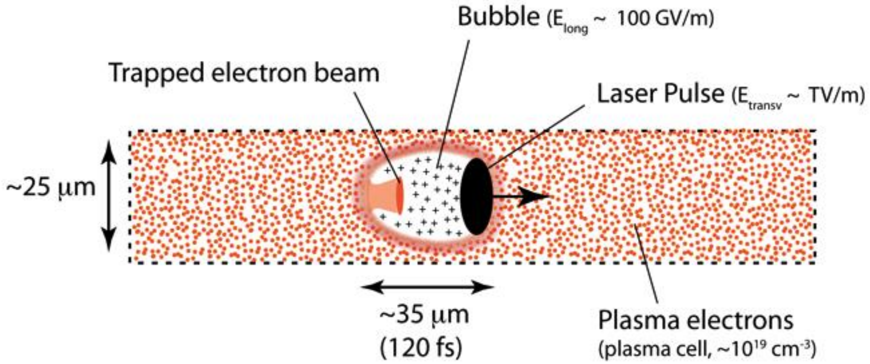
E. Barzi, Snowmass '21





Machine	E_{e^-} (GeV)	N_{e^-} (nC)	Polarization	N_H/yr	N_{Hadronic}/N_H	$N_{\text{minbias/BX}}$
XCC	62.8	1.0	90% e^-	34,000	170	9.5
OCC	86.5	1.0	90% e^-	30,000	540	50
ILC	125	3.2	-80% e^- +30% e^+	42,000	140	1.3
ILC	125	3.2	+80% e^- -30% e^+	28,000	60	1.3

Advanced Accelerators: Plasma

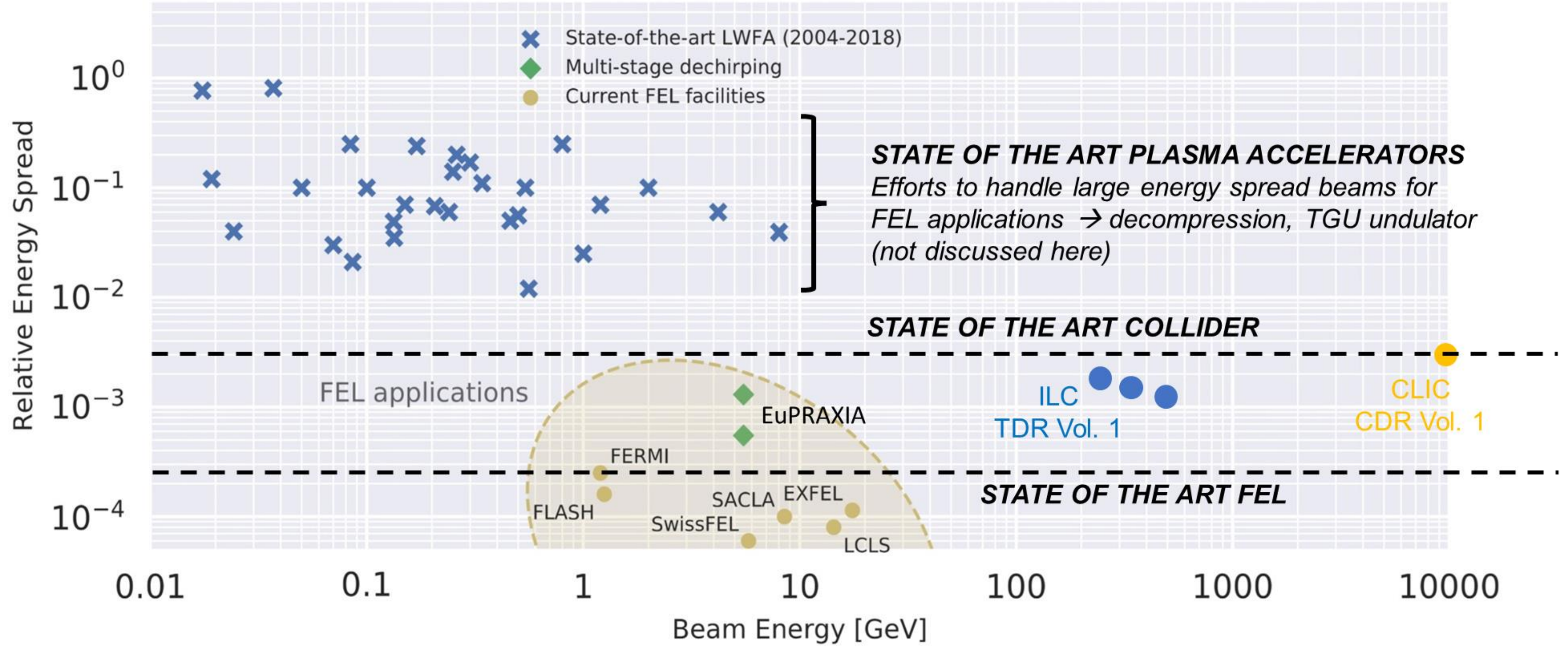


R. Assmann

A plasma cell compared with the superconducting accelerator FLASH (credit DESY)

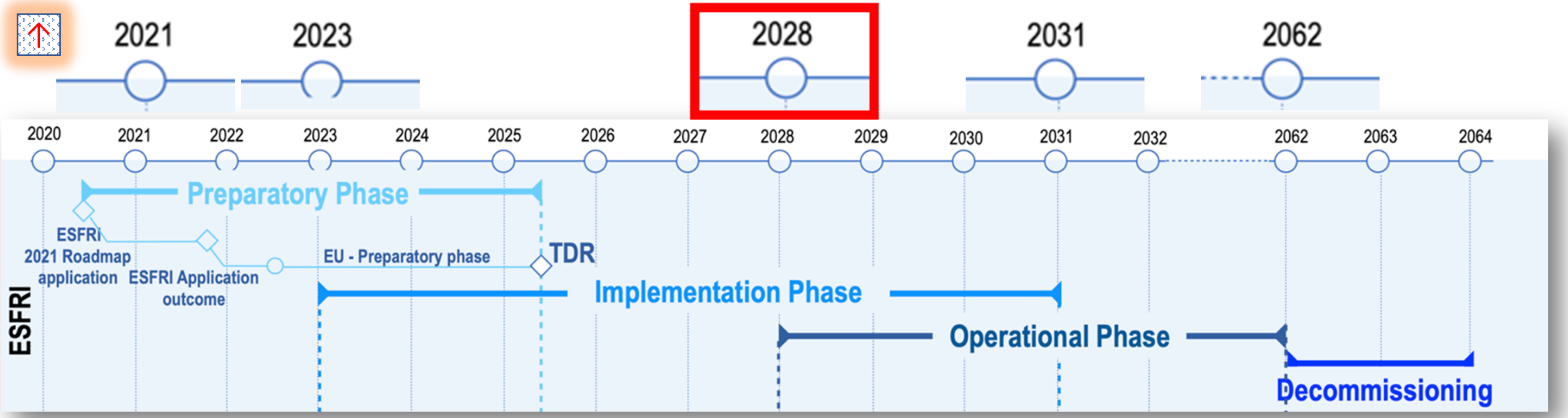
R. Assmann, E. Gschwendtner, R. Ischebeck, LDG Draft

Advanced Accelerator "Demonstrator" EuPRAXIA



R. Assmann,
iFAST BWS2022

construction
at INFN-LNF



Plasma Accelerator Challenge: Positron Acceleration

"ballistic injection": a ring-shaped laser beam and a coaxially propagating Gaussian laser beam are employed to create donut and center bubbles in the plasma, resp.

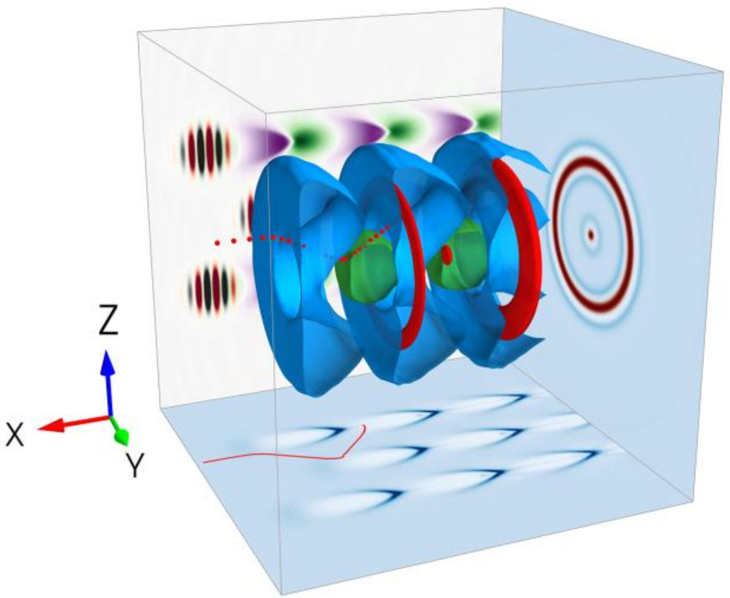
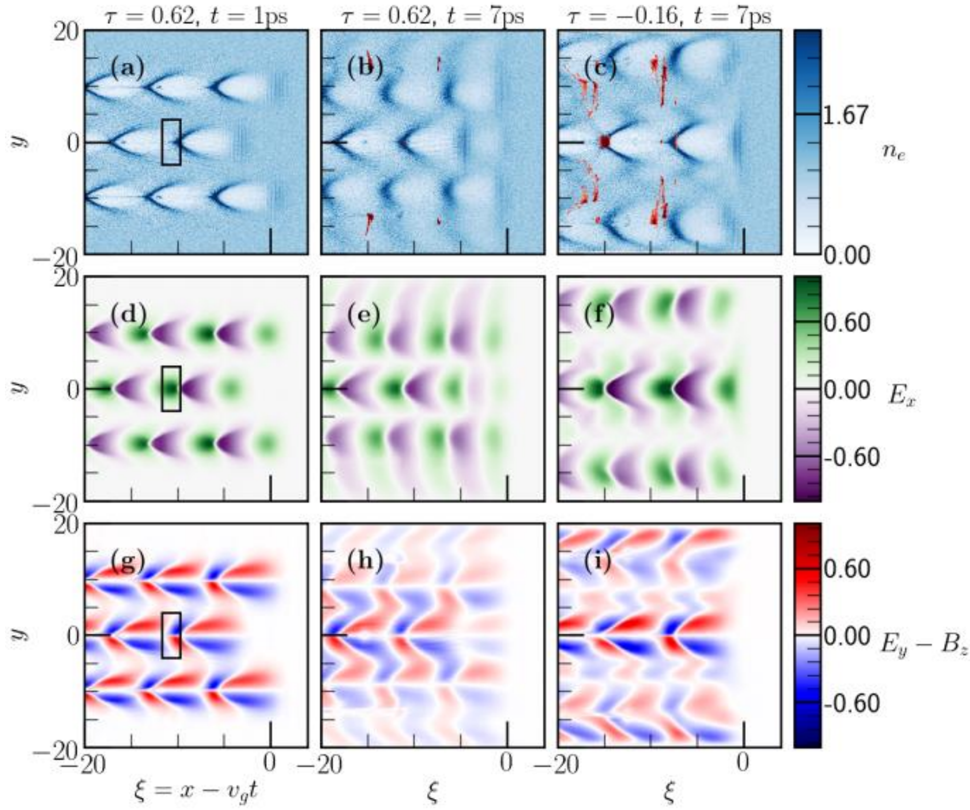


FIG. 1. The concept of the positron ballistic injection scheme. The blue and green colors are contour surfaces of electron densities of donut and center bubbles, respectively. The red color represents injected positrons. The x–y and x–z planes are transverse slices of the density distribution and the longitudinal electric field E_x. The red curve in the x–y plane is the trajectory of an injected positron (corresponding to the projection of red balls in the 3D model). The leading oscillating colors (amber and grey) denote the laser beams in the x–z plane. The y–z plane is the projection of electron density (blue) and injected positron density (red).



PHYSICAL REVIEW ACCELERATORS AND BEAMS **23,** 091301 (2020)

New injection and acceleration scheme of positrons in the laser-plasma bubble regime

Z. Y. Xu,[1] C. F. Xiao,[1] H. Y. Lu,[1,2,3,*] R. H. Hu,[1,†] J. Q. Yu,[1,‡] Z. Gong,[1] Y. R. Shou,[1] J. X. Liu,[1] C. Z. Xie,[1] S. Y. Chen,[1] H. G. Lu,[1] T. Q. Xu,[1] R. X. Li,[4] N. Hafz,[5] S. Li,[5] Z. Najmudin,[6] P. P. Rajeev,[7] D. Neely,[7] and X. Q. Yan[1,3]

Z.Y. Xu

Advanced Accelerator Types

Required parameters for a linear collider with advanced high gradient acceleration [R. Assmann]. Three published parameter cases are listed. This table is taken from the LDG report [N. Mounet (ed.), "European Strategy for Particle Physics - Accelerator R&D Roadmap", arXiv:2201.07895 CERN-2022-001]

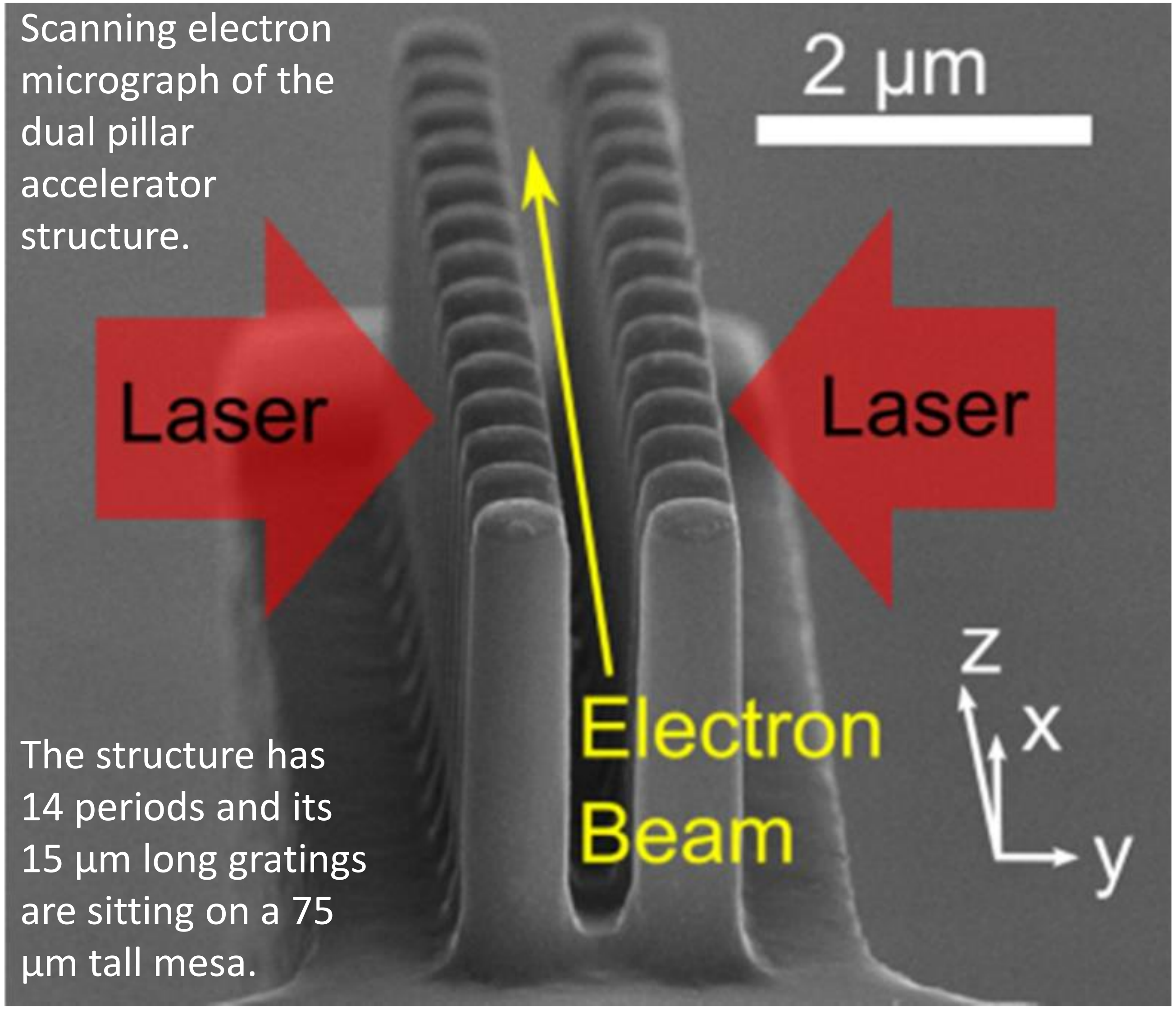
Parameter	**Unit**	**PWFA**	**LWFA**	**DLA**
Bunch charge	nC	1.6	0.64	4.8×10^{-6}
Number of bunches per train	-	1	1	159
Repetition rate of train	kHz	15	15	20,000
Convoluted normalized emittance ($\gamma\sqrt{\epsilon_h\epsilon_v}$)	nm-rad	592	100	0.1
Beam power at 5 GeV	kW	120	48	76
Beam power at 190 GeV	kW	4,560	1,824	2,900
Beam power at 1 TeV	kW	24,000	9,600	15,264
Relative energy spread	%		$\leq$0.35	
Polarization	%		80 (for e^-)	
Efficiency wall-plug to beam (includes drivers)	%		$\geq$10	
Luminosity regime (simple scaled calculation)	$10^{34}cm^{-2}s^{-1}$	1.1	1.0	1.9

Dielectric Laser Accelerators (DLAs) may help explore the dark sector

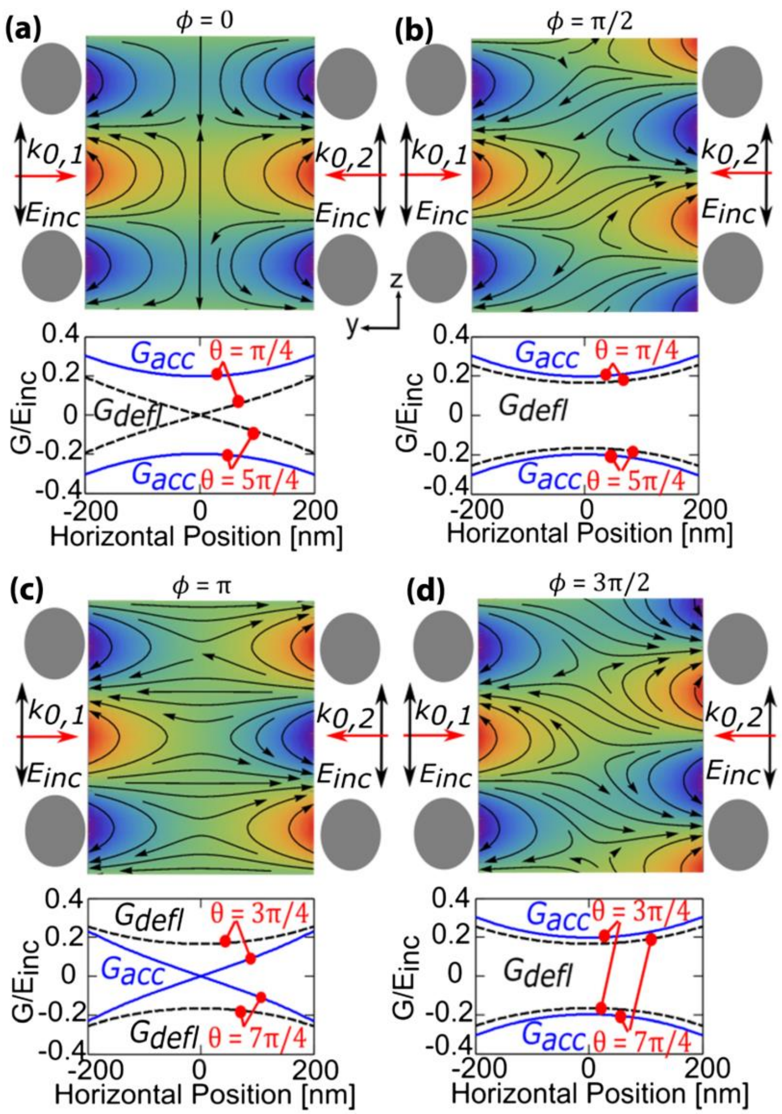
The insets show the accelerating and deflecting gradients across the channel for illustrated optical phases θθ.

Dielectric Laser Accelerators

Scanning electron micrograph of the dual pillar accelerator structure.



The structure has 14 periods and its 15 µm long gratings are sitting on a 75 µm tall mesa.

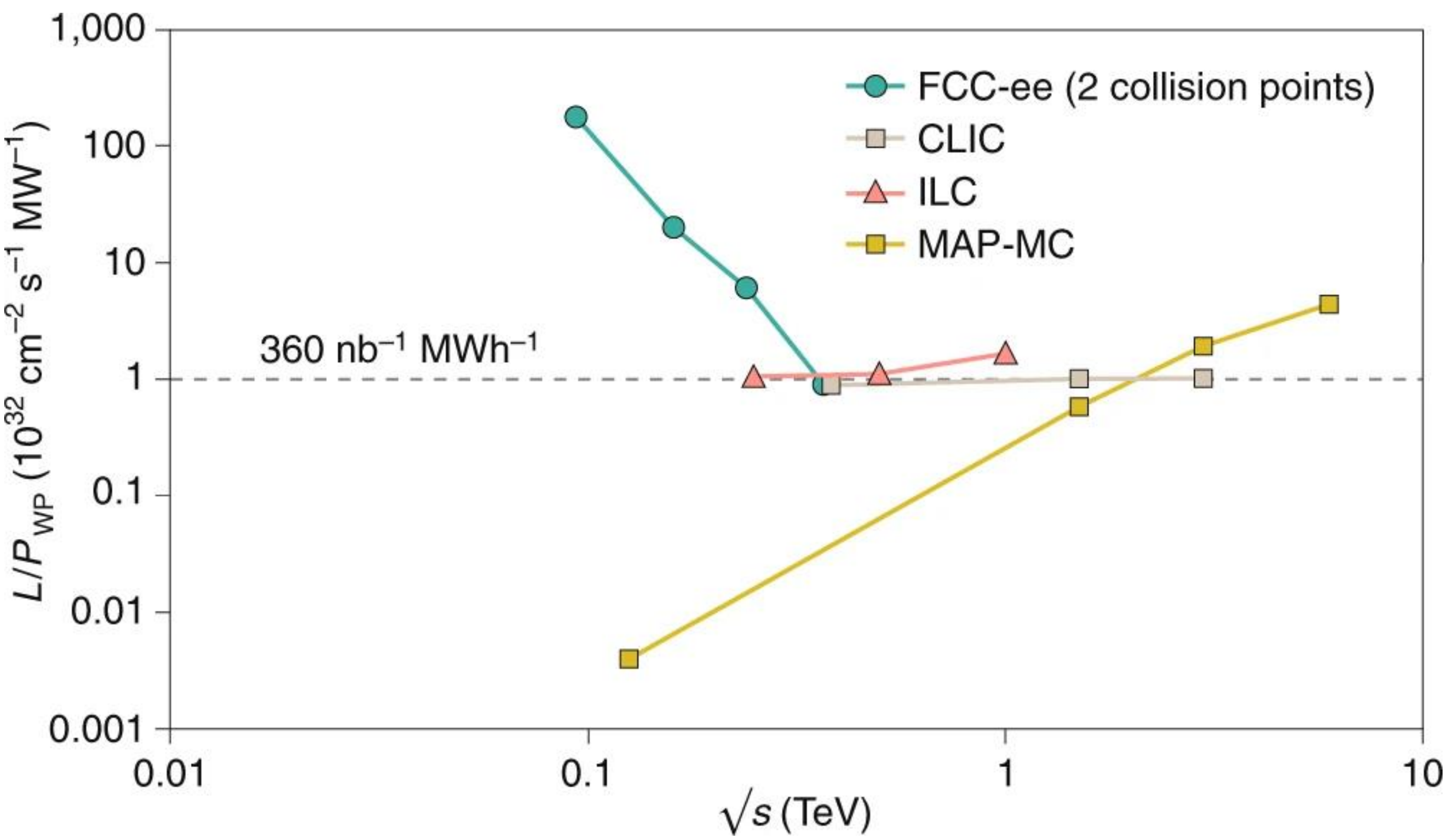


Dual pillar dual-drive mode profiles with force vectors superimposed on the Ez acceleration field color map at different relative drive phases. Insets show accelerating and deflecting gradients across channel for illustrated optical phases θ.

Kenneth J. Leedle, Dylan S. Black, Yu Miao, Karel E. Urbanek, Andrew Ceballos, Huiyang Deng, James S. Harris, Olav Solgaard, Robert L. Byer, "Phase-dependent laser acceleration of electrons with symmetrically driven silicon dual pillar gratings," Opt. Lett. **43,** 2181-2184 (2018); https://www.osapublishing.org/ol/abstract.cfm?uri=ol-43-9-2181

back to the next generation

Energy efficiency: Higgs factories



Total luminosity per electrical power. (Nature Physics vol. 16, 402, 2020)

Carbon Footprint - examples

TWh / year for the "Higgs factory" centre-of-mass energy

Patrick Janot

$\sqrt{s}$ = 240 GeV for CEPC/FCC-ee, 250 GeV for ILC/C3, 380 GeV for CLIC

CLIC	ILC	C3	FCC-ee	CEPC
0.8	0.9	0.9	1.1	2.0

P. Janot and A. Blondel, *The carbon footprint of proposed e+e− Higgs factories*, arXiv 2208.10466 (2022); https://arxiv.org/abs/2208.10466

Energy consumption in MWh / Higgs

CLIC	ILC	C3	CEPC	FCC-ee
30	20	21	10	3.3

becomes 2 MWh / Higgs for FCC-ee with 4 IPs

Present carbon footprint for electrical energy in tons CO_2 / Higgs

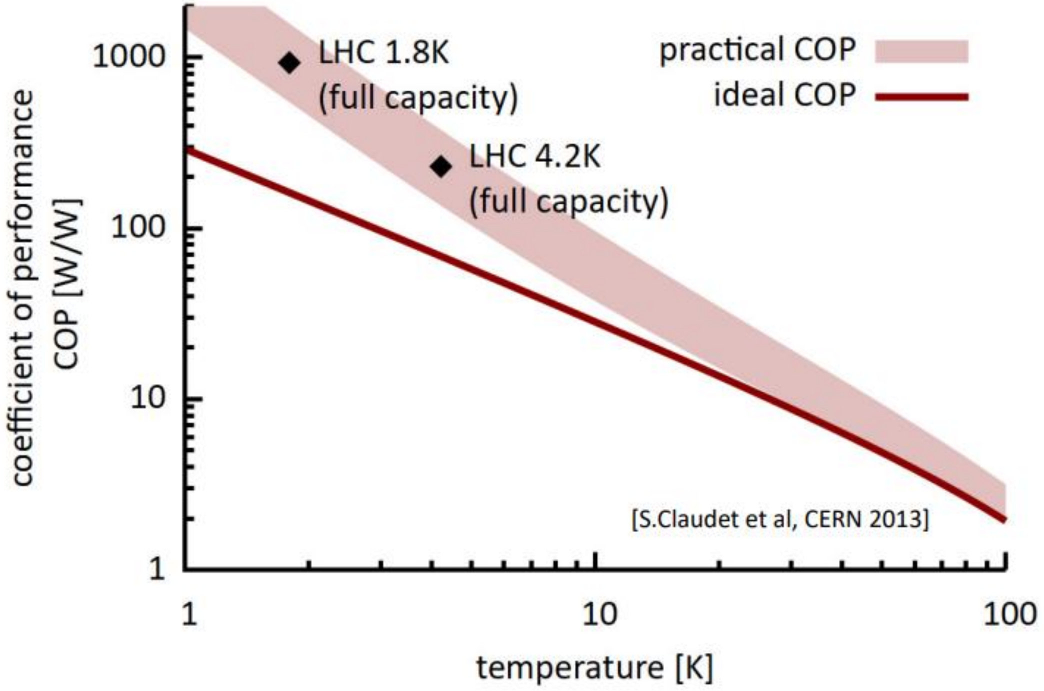
CLIC@CERN	ILC@KEK	C3@FNAL	CEPC@China	FCC-ee@CERN
2.1	7.8	8.5	6.1	0.24

0.14 ton CO_2 / Higgs for FCC-ee with 4 IPs

Futher sustainability considerations

Higher magnet temperature helps

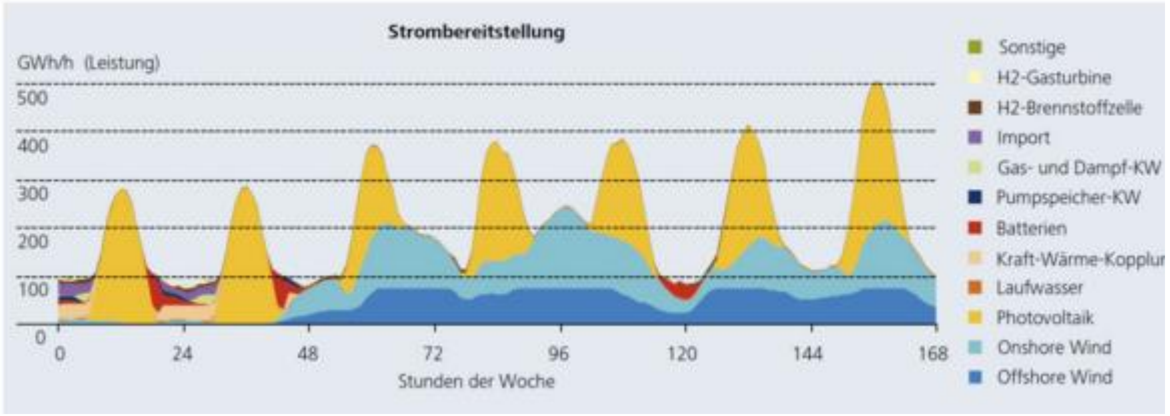
1.9 K Nb-Ti or Nb_3Sn magnets
→ 4.5 K/20 K Nb_3Sn/HTS magnets



still far from ideal Carnot efficiency

Future: fluctuating energy sources

Simulation for Germany 2050



full collider operation at times of high grid production

reduced operation or standby modes with fast L recovery otherwise

varying #bunches in circular colliders

M. Seidel

A few conclusions

- Great progress in SC RF and in high-field magnets
- Accelerators & colliders getting ever more efficient
- Synergies with other applications and other fields
- Numerous innovative concepts and challenges for future colliders
- Sustainability has become important design criterion
- Several promising paths forward

surely great times ahead !